Design guide for Power tapping from Extra-high Voltage (EHV) lines using insulated shield-wire and series compensation, with standardised components

by

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DECLARATION

I, Rikus Lategan, hereby declare that this research project submitted for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: ELECTRICAL, is my own independent work that has not been submitted before to any institution by me or anyone else as part of any qualification.

R. LATEGAN
SIGNATURE OF STUDENT

20/10/98
DATE

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SUMMARY

The technology for tapping power from Extra-high Voltage (EHV) lines by using an insulated shield-wire and series compensation, has already been developed. This technique is known as CAPTAP.

The CAPTAP technology's main target area is in sparsely populated areas where people are living next to an Extra-high Voltage line and do not have the benefit of electricity. The technology can only supply approximately 50kW of power. With this low kilowatt capacity per substation and thus a very low revenue, it is essential to develop a CAPTAP system as cost-effective as possible.

With the CAPTAP development up to date, a new shunt capacitor and reactor value had to be determined for each new CAPTAP substation design, without any standardisation on these components.

The aim of this study is to design and build future low-cost CAPTAP substations, by using standardised components with the absolute minimum computer usage.

There was a serious need to construct a CAPTAP substation in a sparsely populated area after the prototype built by Leigh Stubbs of Eskom Transmission Department in 1992. Unfortunately the Prototype CAPTAP was not situated close to any domestic customers who have not yet experienced the benefit of electricity.

Eskom management agreed to subsidise a Pilot CAPTAP substation, on condition that the cost be kept as low as possible. The author took the initiative to design and construct a proper low-cost substation in an area that justifies this kind of technology. It was decided that the equipment from the prototype substation would be re-used in order to build a Pilot CAPTAP substation.

Having had the opportunity of building a Pilot CAPTAP substation, the author designed a new improved off-ground level low-cost substation.

With the experience gained from this field exercise, the author developed a new method of designing a CAPTAP system with standardised components and without in-depth computer simulations.

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UITTREKSEL

Die bestaande tegnologie vir die aftapping van krag vanaf Ekstra Hoë Spanningslyne deur middel van die insulering van een aardgeleier en seriekompensasie, staan bekend as CAPTAP.

Die CAPTAP tegnologie se hoof teikenarea is yl bewoonde gebiede waar mense reg langs Ekstra Hoë Spanningslyne woon, en nie die voordele van elektrisiteit kan geniet nie. Die tegnologie kan slegs ongeveer 50kW lewer. Met hierdie lae kilowatt kapasiteit per substasie en dus 'n baie lae inkomste, is dit noodsaaklik om die CAPTAP-stelsel so koste-effektief moontlik te ontwikkel.

Met die huidige CAPTAP-ontwikkeling word 'n nuwe parallel-kapasitor en 'n reaktorwaarde vir elke nuwe CAPTAP-substasie bereken, sonder dat daar enige standaardisering plaasvind.

Die doel van die studie is om nuwe lae-koste substasies te ontwerp en te bou deur gebruik te maak van gestandaardiseerde komponente met so min moontlike gebruik van rekenaars.

Daar het 'n geweldige behoefte ontstaan om 'n CAPTAP-substasie in 'n yl bewoonde gebied te bou, nadat die prototipe CAPTAP-substasie deur Leigh Stubbs gebou is in 1992. Ongelukkig was die prototipe CAPTAP nie geleë in 'n huishoudelike omgewing met kliënte wat nog nie die voordeel van elektrisiteit geniet nie.

Eskom-bestuur het ingestem om die loods CAPTAP-substasie te subsidieer, op voorwaarde dat die koste so laag as moontlik gehou moet word. Die skrywer het die inisiatief geneem om 'n lae-koste CAPTAP-substasie te ontwerp en te bou in 'n area wat die tipe tegnologie regverdig. Om koste te bespaar is daar besluit om die toerusting van die prototipe CAPTAP-substasie te hergebruik.

Die skrywer het met die geleentheid om 'n lae-koste substasie te bou, 'n nuwe lae-koste paalgemonteerde substasie ontwerp.

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Met die ondervinding wat die skrywer tydens hierdie veld-oefening opgedoen het, het hy 'n nuwe metode vir die ontwerp van 'n CAPTAP-stelsel ontwikkel, met gestandaardiseerde komponente en sonder ingewikkelde rekenaarsimulasies.

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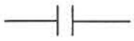
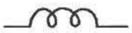
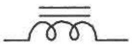
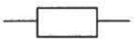
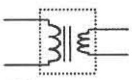
LIST OF ABBREVIATIONS

A	Ampere
AC	Alternating-Current
C	Capacitance
DC	Direct Current
Fo	Frequency at Resonance
HV	High Voltage
H	Henry
l	Inductance
km	kilometer
kV	kilovolt
kVA	kilovolt-ampere
kW	kilowatt
LV	Low Voltage
µF	Micro Farad
MOV	Metal Oxide Verister
nF	Nanofarad
O/C	Overcurrent
R	Resistance
SEF	Sensitive Earth Fault
SWER	Single-wire Earth Return
V	Volt

LIST OF SYMBOLS

	Ampere meter
∠	Angle
	Capacitance
 Is	Current Source
	Current or Voltage Direction
	Earth point
°	Degrees
	Inductance
	Inductor with an iron core
	Isolator Switch
	Load
Ω	Ohm
	Resistance
	Thyristor
	Transformer
 Vs	Voltage Source

CHAPTER ONE

INTRODUCTION

1.1 PROBLEM STATEMENT

The frustration experienced by rural people living close to Extra-high Voltage (EHV) lines in rural areas, who do not have the benefits of electricity, is a well-known problem. The building of a step-down substation with an Extra-high Voltage transformer is extremely costly and will amount to approximately R 7 million. This is too expensive for the general farmer or small community.

On an Extra-high Voltage line typically four to five hundred Megawatts of power flows. It is therefore not desirable to take the risk of connecting a very small customer of approximately 20 kilowatts to an Extra-high Voltage line. The small customer may experience a fault which could result in a total failure of the Extra-high Voltage line. This could lead to a Power loss in a whole region.

A technique for harnessing the power in the overhead shield-wires has been developed to produce an alternative rural electricity supply. The technique known as CAPTAP, is a technique where power is tapped by means of capacitive coupling [16]. The technique makes use of passive series compensation to achieve an acceptable voltage regulation on the output of the power supply and uses the lightning shield-wire of an Extra-high Voltage line as a power source.

Most of the theoretical studies concerning power tapping from High-voltage transmission lines, using insulated lightning shield-wires and series compensation, have been conducted by Leigh Stubbs in his Master's Degree in Electrical Engineering at the University of the Witwatersrand, Johannesburg, in 1994 [16].

In-depth computer simulations were executed to simulate the effect of tapping power from an overhead shield-wire. Calculations were made to determine the series compensation components and a prototype substation was built, after which some basic tests were performed. Even though this technique was tested in some ways, there is no final design guide for the implementation of such a project.

The prototype project was only tested over a short period of time and no real customers were connected to it. The protection makes use of a gas-controlled breaker in order to clear faults, as they occur. Due to gas leaks at the connections over a period of time, the gas control system seems to be not very effective.

Due to the limited number of customers that can be connected to a CAPTAP supply point and the extreme poverty prevalent in these areas, very little revenue will be generated from such a supply point. The cost implication of this project will thus be of great importance, in order to be able to prove the economical viability of the project. The prototype substation was built using a conventional method, with steel medium equipment supports, yard stone and a security fence. This was far too costly for the sparsely populated rural community.

With the CAPTAP development up to date, a new shunt capacitor and reactor value had to be determined for each new CAPTAP substation design, without any standardisation on these components.

1.2 DEMARCATION AND PURPOSE OF STUDY

Figure 1.1 shows the layout of a CAPTAP system from the 400kV transmission line to the end customer.

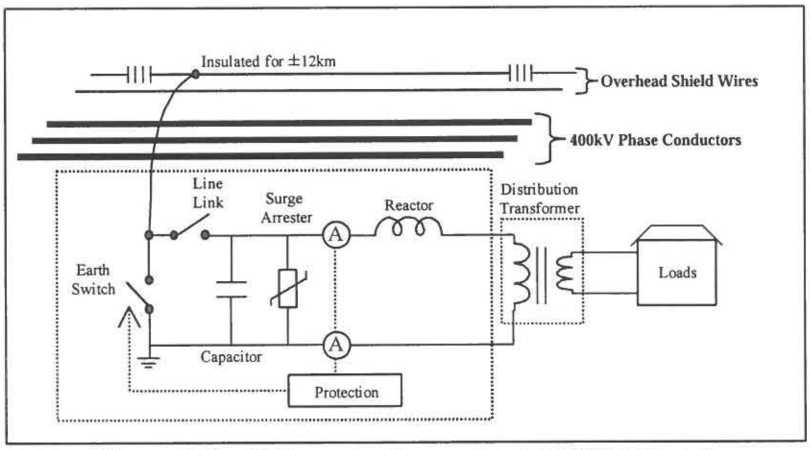


Figure 1.1 : Schematic diagram of CAPTAP system

This project is aimed at deriving a more practical way of implementing the power tapping technique (CAPTAP) from high-voltage transmission lines using insulated lightning shield-wires and series compensation. The aim of this study is to design and build future low-cost CAPTAP substations, by using standardised components with the absolute minimum computer usage.

Instead of relying on a computer simulation to determine the source impedance components, the study will tend to measure the source impedance and to determine the source and reactive compensation components by using simple calculations.

This whole concept must be tested in the rural communities and for the specific application of farmers in the Northern Cape area, where a 400 kV line is located across the farmer's property, especially where rural lines are too far away and more costly to erect, and where voltage problems may occur.

Due to the expensive construction of the prototype substation described in paragraph 1.1, it is necessary to take an overview of the original design of the prototype substation and design a low-cost version of this type of substation.

The implementation of a CAPTAP system will contribute to the electrifying of sparsely populated areas such as the Northern Cape region of South Africa at a low cost.

Further savings can result by expanding the CAPTAP and combining it with Single-wire Earth Return (SWER) systems, as it will reduce the cost by only using one over-head wire.

The provision of electricity to rural households and communities will lead to a significant improvement in the quality of life and will result in the social upliftment of these people [8].

With the project implemented in a farming environment, it will be essential to do some practical tests on pumping, welding and household applications. During these tests, measurements for harmonics, voltage dips and stability will be executed, to prove whether this method of power tapping is viable or not.

This study will contribute to South Africa's Reconstruction and Development Programme (RDP), to electrify 2.5 million households and schools by the year 2000 [8].

1.3 UNIQUENESS OF THIS STUDY

This power source differs from any of the conventional types of power sources used by Eskom in South Africa. It is different in the sense that no conventional transformer is used to step the Extra-high Voltage (400kV) down to a sub-transmission Voltage (132kV) and then down to a usable Reticulation voltage (11 or 22kV).

By making use of the insulated overhead shield-wire and reactive series compensation, a rural supply can be established where only an Extra-high Voltage line is available.

1.4 HYPOTHETICAL SOLUTION

Power tapping from Extra-high Voltage (EHV) lines for commercial applications, using insulated shield-wires and series compensation, can be achieved by making use of standardised series compensation components.

1.5 SUMMARY

Chapter One describes why this project was initiated and what the specific aims for this project are. This chapter also demarcate the study area and states the hypothetical solution for this study.

Chapter Two consists of a literature study of previous work done on the use of overhead shield-wire as a power source. Calculated equivalent source parameters and thyristor controlled compensation are described.

Chapter Three describes a number of basic concepts, which will be referred to further through this thesis, i.e. electromagnetic and electrostatic coupling, ferro-resonance and series and parallel resonance. This chapter also provides an overview of the design, erection and the problems experienced while the Prototype CAPTAP substation was built.

Chapter Four provides a step-by-step design guide from which a CAPTAP substation can be designed and erected. The Component Value Spreadsheet is described in detail, in order to use standardised component values and series compensation for future CAPTAP substation designs. By using the Component Value Spreadsheet, a CAPTAP system with a natural resonant frequency of 50Hz can be obtained.

Chapter Five describes the methods, problems and design alterations experienced by the author, while building the Pilot CAPTAP substation. The Component Value Spreadsheet from Chapter Four was applied and the requirements for a tuned CAPTAP system were determined.

Chapter Six describes some after commissioning experiments to prove the CAPTAP system.

Chapter Seven provides a conclusion with general discussions and define areas for future research.

CHAPTER TWO

LITERATURE OVERVIEW

2.1 INTRODUCTION

Chapter One described why this project was initiated and what the specific aims for this project are. Chapter One also demarcates the study area and states the hypothetical solution for this study.

Chapter Two will consist of a literature study of previous work done on the use of overhead shield-wire as a power source. Calculated equivalent source parameters and thyristor controlled compensation will be described. This chapter is a literature study about the utilisation of Shield-wire power tapping used by BG Checo and Hydro-Quebec in Canada [1][5]. Aspects like design philosophies, benefits from such a system, voltage regulation, and some examples of previous installations will be covered in this chapter.

2.2 BACKGROUND

Many developing countries (particularly in Africa) are faced with the challenge of distributing electricity as cheaply as possible, particularly in the rural areas. In many areas in South Africa a fairly well developed High-voltage network exists, yet rural communities often close to such High-voltage systems are not yet served. This is mainly due to the high cost of establishing distribution networks and also due to the system security and reliability trade-offs. The small, sparsely distributed loads cannot justify the high cost.

One of the key strategic initiatives adopted by Eskom, the National Utility, is that of "Electricity for all". In urban areas, the sheer volume of connections makes achieving this goal cost-effective, however, in the sparsely populated rural areas this is not the case. Consequently innovative design techniques to achieve "low-cost" rural electrification are actively being sought.

It is particularly frustrating for people living close to high-voltage transmission lines while they do not have access to electricity. This problem was highlighted when (in 1992) ESKOM had difficulties in acquiring a 400 kV line servitude from farmers in the Eastern Cape region who have no electricity.

The presence of electrical energy in the overhead shield-wire on transmission lines has been known for many years. It's possible utilisation in remote areas offers many advantages, but due to technological problems, access to this energy source was unfortunately very difficult. Hydro-Quebec, a utility interested in this energy source, asked its Research Institute to carry out studies to determine whether this energy could be harnessed. This resulted in a system which could tap small amounts of electrical power from high-voltage transmission lines. Systems were developed to supply power to seventeen microwave repeater stations along the 735 kV line between James Bay and Montreal [2]. These systems use the lightning shield-wires which, when insulated from the towers, have a capacitively-induced voltage on them. This capacitively-induced energy is converted into usable electricity by means of reactive compensation. Other alternatives that were evaluated but found to be less suitable for this application, were diesel generators, solar panels and small hydro turbines.

Leigh Stubbs of Eskom Transmission Substation Technology [16] designed a system that uses a technique of series compensation for tapping power from insulated lightning shield-wires. This technique requires no electronics for voltage regulation as does the Canadian system and is therefore more cost-effective.

2.3 BENEFITS OF CAPTAP SYSTEM

2.3.1 ELECTRIFICATION

The electrification program supplying low-cost power to underdeveloped areas can be extended to areas where it had not been feasible in the past.

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2.3.2 SOUTHERN AFRICAN GRID

Direct benefit can be given to communities adjacent to transmission lines in neighbouring countries. This will preserve the goodwill of these inhabitants and thus possibly curb vandalism and sabotage to the transmission line.

2.3.3 SERVITUDE ACQUISITION

It may be easier to acquire servitude from farmers and landowners if they can benefit from the transmission lines.

2.4 REVIEW OF PREVIOUS WORK

Most of the work on the concept of tapping power from insulated lightning shield-wires on transmission lines has been carried out by "Institut de Recherche" of Hydro Quebec (I.R.E.Q.) and BG Checo International in Canada [6] [14].

There are two main areas of interest in deriving power for insulated shield-wires. Firstly the equivalent source parameters of the insulated lightning shield-wire has to be known, and secondly a system has to be designed to regulate the output voltage of this supply.

2.4.1 SHIELD-WIRE EQUIVALENT SOURCE PARAMETERS

Before designing a shield-wire supply system, it is important to understand the relationship between the physical dimensions of the transmission line conductors and the equivalent source parameters of the insulated section of shield-wire. This will enable the designer to optimise the design and later pin-point errors.

There are two papers of relevance in this area. One is based on the research of I.R.E.Q. (Maruvada and Harbec, 1978) [14] covering transmission voltages between 300 kV and 750 kV, and the other on the research by the Indian Institute of Science (Gururaj and Nandagopal, 1970) [5] covering transmission voltages between 66 kV and 220 kV.

The purpose of Gururaj and Nadagopal's paper is to provide a simplified method for calculating the equivalent circuit parameters for an insulated shield-wire (insulated for power tapping) on a transmission line up to 220 kV.

Gururaj and Nandagopal give the general equations relating to the potentials on a system of parallel conductors to the charges (per unit length) on the conductors. These quantities are related to the electrostatic coefficients of the conductors, which can be derived from the geometrical dimensions of the system of conductors. The relationships are given by the following matrix equations:

$$V(i) = P(i,j) \bullet Q(i) \qquad (2.1)$$

$$Q(i) = P^{-1}(i,j) \bullet V(i,j) \qquad (2.2)$$

where:

$P^{-1}(i,j) = C(i,j)$

V(i) = Potential array

P(i,j) = Electrostatic coefficient matrix (nxn matrix for n conductors)

Q(i) = Charge array

C(i,j) = Capacitance matrix

By using the theory where charged conductors with opposite charges mirror conductors in the earth plane, the elements in the electrostatic coefficient matrix can be defined by the following equations:

$$P_{ii} = \frac{1}{2\pi\varepsilon_0} \bullet \ln\left[\frac{S_{ii}}{r_i}\right] [F^{-1}\ m] \qquad \text{(Diagonal Elements)} \qquad (2.3)$$

$$P_{ij} = \frac{1}{2\pi\varepsilon_0} \bullet \ln\left[\frac{S_{ij}}{s_{ij}}\right] [F^{-1}\ m] \qquad (2.4)$$

where:

ε_0 = Permativity constant = $10^{-9} / 36\pi$

P_{ii} = Self-electrostatic coefficient

P_{ij} = Mutual electrostatic coefficient

S_{ij} = Distance between conductor i and the image of conductor j

S_{ij} = Distance between conductor i and conductor j

R_i = Radius of conductor i

Gururaj uses these equations to derive the Thèvenin equivalent model for a single insulated lightning shield-wire for both single-circuit and double-circuit lines. The influences of various geometrical parameters (of the transmission line) on the Thèvenin equivalent model parameters are presented graphically for a range of transmission line configurations (66 kV to 220 kV). A simplified method is given for calculating the induced voltage on the shield-wire and the equivalent capacitance (Thèvenin equivalent model), using the graphs presented.

In one experiment Maruvada and Harbec (1978) [14] explored the possibility of using two shield-wires instead of one to tap power from transmission lines. A two-port network equivalent circuit model consisting of two voltage sources and three capacitances is derived, which represents the two-shield-wire-source. The equivalent model is used to derive (derivations not shown) the equations for maximum power to supply a resistive load. The following alternative configurations for shield-wire loading are considered:

- One wire loaded with the other isolated,
- One wire loaded with the other earthed,
- Both wires loaded independently, and
- Both wires connected in parallel to a load.

The purpose of their study was to find the loading configuration, which would give the highest power output per unit length of insulated shield-wire. It can be shown that maximum power can be tapped if one shield-wire is earthed and the other loaded.

Maruvada and Harbec then used a set of matrix equations to derive the network equivalent circuit parameters. A computer program was used to generate a set of graphs (using the matrix equations) relating the equivalent circuit parameters to the physical parameters of a range of transmission line configurations (300 to 750 kV). Similar conclusions to those of Gururaj and Nandagopal were reached concerning these relationships.

These two papers deduce the following general conclusions concerning the above relationships:

2.4.1.1 Induced Voltage

The equivalent open-circuit voltage on an insulated lightning shield-wire is influenced by the following factors:

- The geometrical position of the insulated shield-wire relative to the other shield-wire and the phase conductors has the greatest influence. This includes the vertical and horizontal displacements.

- The individual diameters of the shield-wire and phase conductors have little influence on this parameter.

2.4.1.2 Source Impedance

The source impedance is described and influenced as follows:

- The source impedance is almost purely capacitive.

- The shield-wire diameter has the largest influence; increase in capacitance results from an increase in diameter.

- The relative positions of the conductors have significant influence.
- The diameters of the phase conductor have negligible influence.

2.4.1.3 Source Parameter Derivation Methods

Before designing a power tap-off system, it is necessary to determine the equivalent shield-wire source parameters for a particular transmission line. A simplified method is presented by Gururaj and Nandagopal (1970) that makes use of graphs to determine the deviations in the equivalent source parameters, from a reference case. It is assumed that the relationships are all linear so that the deviations can be summated together with the reference case parameters in order to get the required source parameters. As this method was devised as early as 1970, it may have been useful in times when computing capabilities were not as accessible to designers as they are now. The method described is only suitable for transmission lines in the range from 66 kV to 220 kV.

It is now considered more desirable to use standard computer packages for computing these parameters. The **Alternative Transients Program (ATP)** was used in the design of the "CAPTAP" series compensation tapping method.

2.4.2 VOLTAGE REGULATING SYSTEMS

There are two basic requirements in order to achieve a suitable power supply. Firstly the output voltage should be standard, so that standard equipment and appliances can be used. Secondly the output voltage should be relatively constant with varying load magnitudes and phase angles (power factors).

I.R.E.Q. and BG Checo in Canada have done much research in this field. The literature, which consists of papers as well as internal reports, describes a number of systems that have been developed and implemented. The literature describes the use of insulated shield-wires as well as directly coupled physical capacitors to tap power from transmission lines. The use of physical capacitors is included in the literature survey as it is electrically similar to the use of insulated shield-wires.

2.4.2.1 Uncompensated supply

Capacitive voltage transformation was used as early as 1971 in order to derive a power supply (Sturton, 1971) [19]. A shunt capacitor divider bank (six 14.4 kV capacitor units, of 2080Ω at 60 Hz, in series; Divider ratio of 6:1) was coupled directly to a 138 kV line and used to supply 75 kW at 13 kV. No reactive compensation was used in this system. This resulted in several problems when a distribution transformer was connected to the capacitor divider:

- **Over voltages and high primary winding excitation currents** due to resonance between the source capacitance and the transformer magnetising impedance, thus resulting in causing saturation of the transformer.
- **High fault current** on the secondary side due to resonance of the source capacitance with the transformer leakage inductance.

These problems were partly overcome by increasing the ratings of the transformer and by having suitable protection settings. The voltage regulation, from no-load to 100 kW for load power factors between 0.90 and 0.85 lagging, ranged between 95% and 118% of rated voltage.

2.4.2.2 Thyristor-Controlled Compensation

I.R.E.Q. devised a system to supply 20 kW to microwave repeater stations along the James Bay 735 kV lines using insulated shield-wires (Berthiaume & Blais, 1977) [2]. Initially no form of reactive compensation was used and the same problems were experienced as described previously. They (Berthiaume & Blais, 1980) later discovered a technique that, by controlling the transformer saturation, could get more power out of the system and could regulate the output voltage to a certain degree (see Figure 2.1). The technique used thyristors connected across the windings of the step-down transformer to shunt current across the winding.

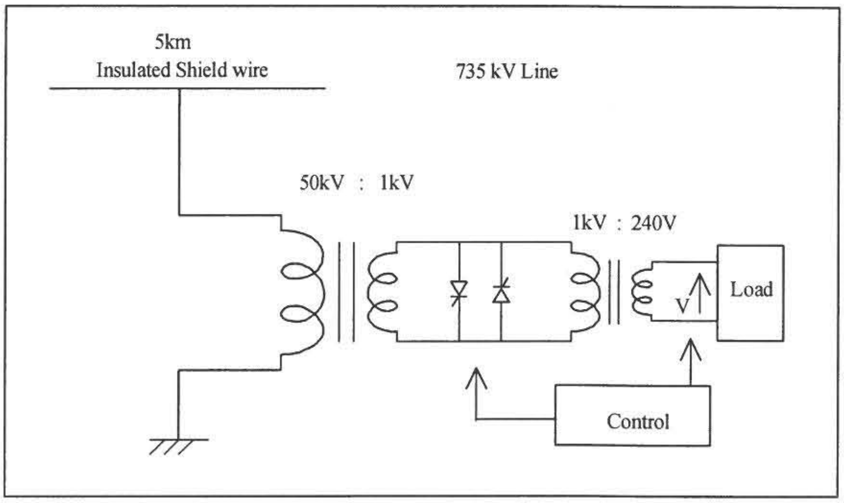


Figure 2.1 : Technique developed by I.R.E.Q to supply 20kW of power

The best technique, which was later developed by BG Checo and I.R.E.Q. (Ruest and Sybille,1990) [12], used a fixed shunt inductor (reactor) in parallel with a thyristor-controlled reactor. By varying the firing angle of the thyristors the degree of compensation could be varied to suit the load conditions (see Figure 2.2).

This technique has more recently been used in single and three-phase supply systems using physical coupling capacitors (see table 2.2). The use of physical capacitors is limited to system voltages up to 275 kV.

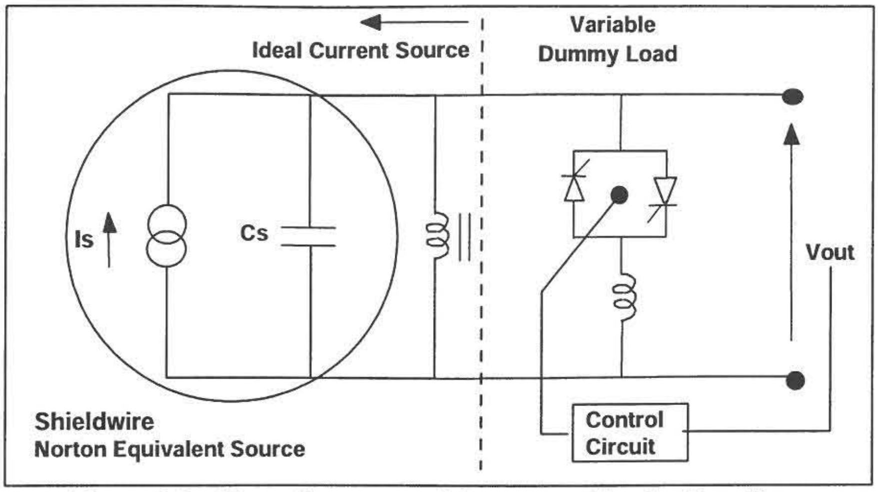


Figure 2.2 : Shunt Compensated Source used by the Canadians

The easiest way to understand the operation of this system is to regard the shield-wire source (Norton equivalent model) together with the fixed shunt reactor, as an ideal current source. The thyristor-controlled reactor (TCR) can be seen as a variable dummy load, which is used to control the output voltage (i.e. TCR fully conducting for no-load condition and open circuit for full-load conditions). The system uses a feedback control system to regulate the output voltage.

Advantages:

- A good voltage regulation (±2%) was achieved using this technique.
- No Ferro-resonance effects were experienced.

Disadvantages:

- The System is expected to operate in remote and uncontrolled environments where access for maintenance to electronic equipment may be difficult.
- Malfunction of the electronic control circuit causes complete failure of the system.

- Thyristor switching generates harmonics, which need to be filtered, thus adding to the cost.

- The cost of the system may be prohibitive.

2.4.3 EXAMPLES OF APPLICATIONS

The following table shows some typical applications of capacitive coupling supply systems as described by Ruest and Sybille (1990) [12]:

Table 2.1 : Typical applications of shield-wire supply systems

Place:	Peru, Nahuimpuquio	Venezuela, Isla infierno	Malaysia, Buta Melingtan
HV Line Voltage	220 kV	760 kV	275 kV
System Frequency	60 Hz	60 Hz	50 Hz
Tower Type	Double cct	Single cct	Double cct
Shield-wire Voltage	21 kV	62 kV	36 kV
Shield-wire length	20 km	3.2 km	40 km
System O/P Voltage	7.2 kV	7.2 kV	6.9 kV
Rated O/P Capacity	70 kVA	35 kVA	100 kVA
Commissioning date	Sep 1982	May 1986	Jun 1987
Application	342 Rural dwellings	Aerial Beacons	450 Rural dwellings

Table 2.2 : Applications of physical coupling capacitor (1 phase) supply systems

Place:	Peru, Langui	Peru, (4 systems) Cerro de Pasco -Tingo Maria line
HV Line Voltage	138 kV	138 kV
System Frequency	60 Hz	60 Hz
Tower Type	Single cct	Single cct
System O/P Voltage	13.8 kV	13.8 kV
Rated O/P Capacity	100 kVA	100 kVA
Commissioning date	June 1987	1 in June 1988 3 in Jan 1990
Application	550 households in 4 villages	1600 households in 4 villages

2.5 SUMMARY

Chapter Two consisted of a literature study of previous work done on using the overhead shield-wire as a power source. Calculated equivalent source parameters and thyristor controlled compensation were described.

Chapter Three will describe a number of basic concepts, which will be referred to further through this thesis, i.e. electromagnetic and electrostatic coupling, ferro-resonance and series and parallel resonance. This chapter will also provide an overview of the design, erection and the problems experienced while the Prototype CAPTAP substation was built.

Central University of Technology, Free State

CHAPTER THREE

SERIES REACTIVE COMPENSATION ALTERNATIVE

3.1 INTRODUCTION

Chapter Two consisted of a literature study of previous work done on using the overhead shield-wire as a power source. Calculated equivalent source parameters and thyristor controlled compensation were described.

Chapter Three will describe a number of basic concepts, which will be referred to further through this thesis, i.e. electromagnetic and electrostatic coupling, ferro-resonance and series and parallel resonance. This chapter will also provide an overview of the design, erection and the problems experienced while the Prototype CAPTAP substation was built.

Leigh Stubbs of Eskom Transmission Substation Technology Department [16] built a prototype CAPTAP substation in 1992.

The prototype CAPTAP substation was erected near Eskom's Apollo substation and power was tapped from one of the lightning shield-wires of the Kendal – Minerva 400kV line.

The prototype substation was erected and tested in many ways, but no permanent customers were connected. Thus the influence of a customers normal day-to-day activities was not tested.

3.2 BASIC CONCEPTS

In this chapter, the following basic concepts will be addressed.

3.2.1 ELECTROMAGNETIC COUPLING

Electromagnetic coupling can best be understood by the coupling of magnetic fields between a transformer's primary and secondary windings. The main criteria for electromagnetic coupling is that a closed loop must be formed (see Figure 3.1). The induced power in the secondary side is directly proportional to the amount of current flowing in the primary side.

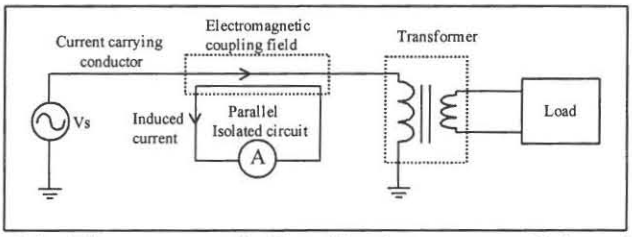


Figure 3.1 : Electromagnetic Coupling between parallel conductors

3.2.2 ELECTROSTATIC COUPLING

Electrostatic coupling is the induced power between an energised conductor and an open-circuit parallel conductor, or can be described as an imaginary capacitor (see Figure 3.2). The magnitude of current flowing in the primary conductor has no effect on the induced power and specifically on the magnitude of the voltage that is induced.

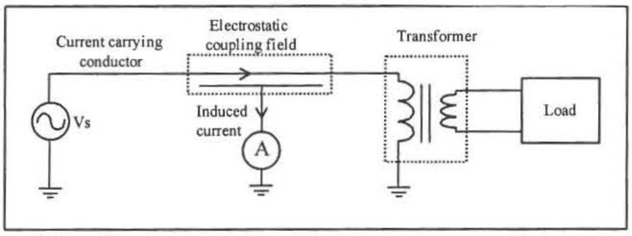


Figure 3.2 : Electrostatic Coupling between parallel conductors

3.2.3 FERRO-RESONANCE PHENOMENON

"Ferro" refers to the steel transformer core.

It is a term describing all oscillatory phenomena occurring in an alternating current electrical circuit consisting of:

- One non-linear inductor, i.e. an inductor with an iron core,
- a linear part with a capacitive component, and
- supplied by one or more sinusoidal voltages.

An example of this is where the exciting reactance of a transformer, which is non-linear, can become nearly equal to the capacitive reactance to ground of a line/cable, due to over voltages, which drives the transformer into saturation.

During core saturation the transformer inductance varies widely with changes in current, thus increasing the chances of reaching a reactance value which equals the cable capacitive reactance.

This point will then be the resonant point, but the resonant point/frequency might not be stable due to the continually changing inductive reactance. These oscillations may be of a transient nature, or may last indefinitely.

High voltages generated by high instantaneous (di/dt) values during energising or de-energising due to contact separation, trigger Ferro-resonance.

Ferro-resonance practically never occurs in normal circuit configuration where transformers have a substantial load connected to them, due to the load damping out the oscillations.

3.2.4 SERIES RESONANCE

With a varying frequency and a constant voltage source, as in Figure 3.3, the amplitude of the current will approach zero at both very low and very high frequencies [9]

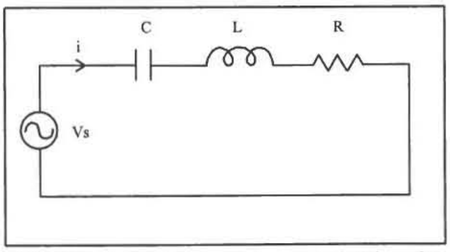


Figure 3.3 : Series Resonant Circuit

The series capacitor blocks the passage of current at very low frequencies, and the series inductor blocks the passage of current at very high frequencies.

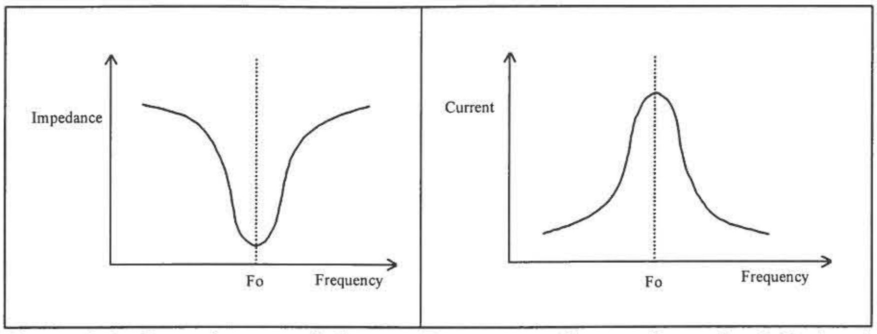


Figure 3.4 : Impedance and Current Resonance Curves for series LC circuit

As shown in Figure 3.4 the amplitude of the current will peak at Vs/R, when the inductive reactance exactly equals and cancels the capacitive reactance. The frequency at which the reactive impedance's cancel, is the resonant frequency of the circuit and is given by :

$$Fo = \frac{1}{2\pi\sqrt{LC}} \tag{3.1}$$

where L = the inductance in the circuit

and C = the capacitance in the circuit

3.2.5 PARALLEL RESONANCE

With a varying frequency and constant current source the following were evident (see Figure 3.5):

At very low frequencies, the inductive reactance of the inductor will be small so the inductor will appear as a very small impedance across the output [9]. Thus the output voltage will be low at very low frequencies. At very high frequencies, the capacitive reactance of the capacitor will be very small and, therefore, will appear as a very small impedance across the output. Consequently, the output voltage will be low at very high frequencies.

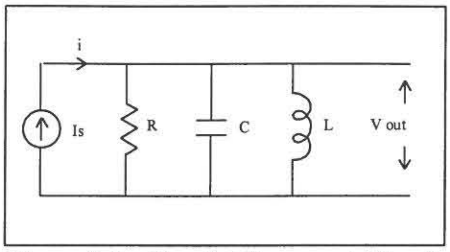


Figure 3.5 : Parallel Resonant Circuit

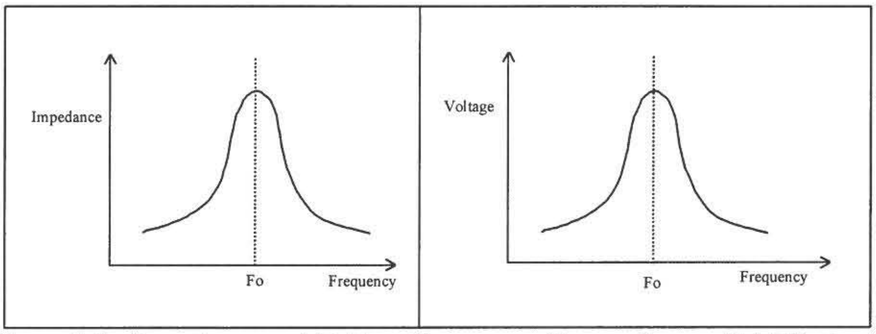


Figure 3.6 : Impedance and Voltage Resonance Curves for parallel LC circuit

As shown in Figure 3.6, the amplitude of the voltage will peak at Is.R, when the inductive reactance exactly equals and cancels the capacitive reactance. The frequency at which the reactive impedances cancel, is the resonant frequency of the circuit and is given by :

$$Fo = \frac{1}{2\pi\sqrt{LC}} \tag{3.2}$$

where L = the inductance in the circuit

and C = the capacitance in the circuit

3.3 SERIES-REACTIVE COMPENSATION

3.3.1 SOURCE PARAMETERS

If a continuous section of one of the overhead shield-wires, of a transmission line, is isolated (i.e. unearthed) from the towers for a certain length, for example 10 km, a voltage source can be derived (see Figure 3.7).

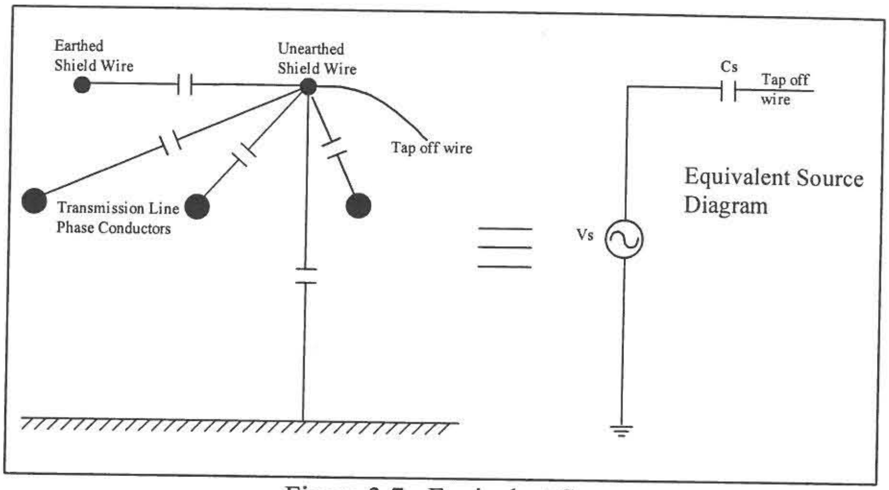


Figure 3.7 : Equivalent Source

The unearthed shield-wire experiences an electrostatic coupling from each of the phase conductors as well as from the adjacent shield-wire. The nearest phase conductor will have the dominant effect of the electrostatic coupling on this unearthed shield-wire. Each electrostatic coupling will be a sinusoidal wave form. Due to the fact that any number of sinusoidal wave forms added together will have a resultant sinusoidal wave form, the induced voltage in the shield-wire will be sinusoidal.

In Figure 3.7, Vs represents the induced voltage on the unearthed shield-wire (i.e. voltage source) and Cs represents the electrostatic coupling with the transmission line (i.e. source impedance).

The Electromagnetic Transients Program (EMTP) is used to simulate the transmission line in order to determine the line constants and the equivalent source parameters Vs and Cs (Figure 3.7). The voltage source is measured in the program, from the "Tap – off" wire, to ground. The source impedance is determined by short-circuiting the insulated shield-wire to ground at one end and then determining the short-circuit current Isc. The source impedance is then determined as follows:

$$Zsource = \frac{Vs}{Isc} \tag{3.3}$$

where Vs = The induced voltage on the shield-wire.

and Isc = The short-circuit current flowing when the shield-wire is connected to ground.

The source impedance is purely capacitive, due to the capacitive coupling to the 400kV phase conductors.

3.3.2 VOLTAGE DIVIDER

Once the source parameters have been calculated, the system can be designed to source a standard output voltage by using the required compensation. To obtain a standard voltage, a physical capacitor Cp is connected from the insulated shield-wire to ground, resulting in a capacitive voltage division (see Figure 3.8). The equivalent source Vs' then becomes the required standard voltage with a new series capacitance equal to the sum of the two capacitances Ct (shield-wire source + physical capacitance).

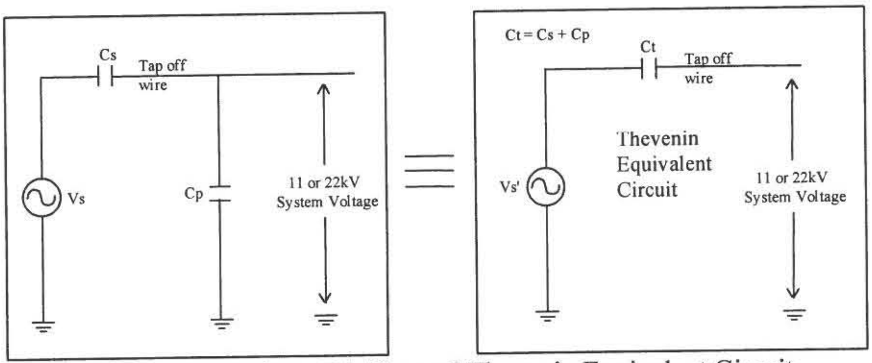


Figure 3.8 : Voltage Divider and Thevenin Equivalent Circuit

This source, however, has a high-series impedance, which is almost purely capacitive. If the source is loaded with a resistive load, the output voltage drops dramatically with an increasing load current.

3.3.3 REACTIVE COMPENSATION

The combined capacitance Ct (in Figure 3.8) now needs to be compensated for by using a suitable fixed inductance (see Figure 3.9). The inductor impedance is selected equal in magnitude to the source impedance at 50Hz, so that the source becomes an "ideal voltage source" at 50 Hz [18].

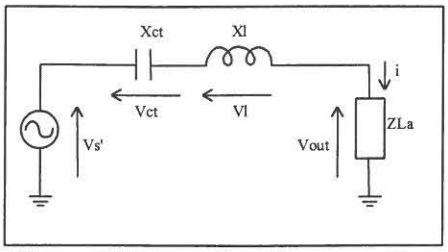


Figure 3.9 : Reactive Compensation

This method of voltage regulation relies on the ability to accurately determine the equivalent source parameters, as the reactor has a fixed value and has to be specified up front.

3.3.4 VOLTAGE STABILITY

The above-mentioned series reactive compensation provides a very good voltage regulation under varying load conditions. The phasor diagram in Figure 3.10 shows clearly that the output voltage is independent of the load current [17].

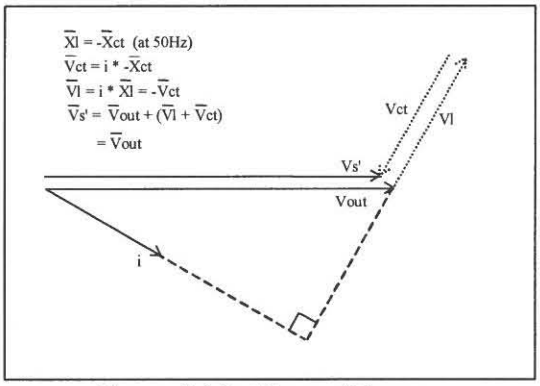


Figure 3.10 : Phasor Diagram

In Figure 3.9 and Figure 3.10 it is clearly shown that the output voltage Vout is equal to the input source voltage Vs', minus the voltage over the capacitor Vct, minus the voltage over the inductor Vl. With the capacitive reactance of the capacitor Xct equal to the inductive reactance of the inductor Xl, at 50 Hz resonant frequency, the two reactive voltages iXct and iXl will cancel each other out. The system will therefore resonate at 50Hz and the only drop in voltage from the source voltage, is over the internal resistance of the inductor, which is negligibly small.

3.4.1 GENERAL APPROACH

The project was started by making use of numerous computer simulations on the Apollo Domain 4000 workstation, using the Alternative Transients Program (ATP).

A 9.6km section of one shield-wire was insulated on the Kendal – Minerva 400kV line. The line was selected, as it had not yet been energised, which made it easier to retrofit insulators on the shield-wire. The distance that was required for the shield-wire to be insulated was determined by computer simulations using the "line constants" routine calculations in order to determine the average conductor height. The formula is as follows:

$$H_{av} = H_{tower} - \{2/3 * (H_{tower} - H_{mid})\} \qquad (3.4)$$

Where H_{tower} = the conductor height at the tower

and H_{mid} = the conductor height at mid span

The two main purposes of the computer simulations were to:

- Establish the equivalent shield-wire source parameters which would be used as the basis for the design of the supply system (to calculate the value of the physical capacitor and reactor), and
- to determine the steady state and transient behaviour of the system in order to calculate the ratings of the equipment and protection settings.

3.4.2 COMPUTER SIMULATION RESULTS AND CALCULATIONS

3.4.2.1 Source Parameters

The computer simulation results were as follows (see Figure 3.7):

Source Voltage $V_s = 47.5kV$

Short-circuit Current $I_{sc} = 1.55A$

Substitude these values into formula (3.3):

$$Zsource = \frac{Vs}{Isc} = \frac{47500\angle 0^{\circ}}{1.55\angle 90^{\circ}}$$

$$= 30645\angle -90^{\circ} = Xcs$$

$$\therefore \quad Xcs = \frac{1}{2\pi fCs} = 30645\Omega$$

$$Cs = 104nF$$

3.4.2.2 Voltage Division

The physical capacitor Cp for a 22kV output voltage will be calculated as follows (see Figure 3.8 and formula (3.3)):

$$Vcp = Vs * \left(\frac{Xcp}{Xcs + Xcp} \right) \tag{3.5}$$

$$\therefore Vcp = Vs * \left(\frac{Cs}{Cs + Cp} \right)$$

$$\therefore Cp = \left(\frac{Vs * Cs}{Vcp} \right) - Cs$$

$$= \left(\frac{47500 * 104nF}{22000} \right) - 104nF$$

$$= 120nF$$

3.4.2.3 Reactive Compensation

The combined capacitance Ct in Figure 3.8 now needs reactive compensation in order to resonate at 50Hz, in order to become an "ideal voltage source". The reactor values are calculated as follows (see Figure 3.9):

$$\text{Xct} = \text{Xl} \ \ \text{(for resonance at 50Hz)} \tag{3.6}$$

$$Xct = \frac{1}{2\pi fCt} = 14210\Omega$$

$$Xl = 14210 = 2\pi fl$$

$$l = 45.2H$$

Assuming a X:R ratio of 50 (at 50Hz) will result in an internal resistance of 284Ω for the reactor.

3.4.2.4 Voltage Regulation and Shield-wire Voltage

In the computer simulation the system was loaded with a 50kVA load with unity power factor and the output voltage dropped from 22kV to 21.3kV. This provides a voltage regulation of 3%.

With the same load the shield-wire voltage increases to 39.8kV from an unloaded voltage of 22kV. With a purely inductive load of 50kVAr (worst case) the shield-wire voltage increases to 54kV, which is very unlikely in practice.

3.4.3 TRANSIENT OPERATION AND OVER VOLTAGE

3.4.3.1 Switching

An electrical supply system needs to be switched ON and OFF, for both operating and protection purposes. Normally this is not a problem, but as this circuit has relatively large energy storage capacity, the switching of the circuit requires careful consideration.

In the prototype, series switching was considered for normal energising, de-energising and protection operations by operating the line link in Figure 3.11. It was found that the voltage, at the instant the current crosses the zero line, is at its peak, due to the 90° phase displacement between the current, and the voltage over the capacitance. This results in a high recovery voltage which causes a flash-over when trying to do switching on the system.

It was found that shunt switching, by closing and opening the earth-switch in Figure 3.11, was the best way of energising and de-energising the CAPTAP substation. By closing the earth-switch, the system is de-energising, and the overhead shield-wire is thus earthed through the earth-switch. The shield-wire voltage tends to be zero again. The steady state current which flows when the shield-wire is earthed, is limited due to the high source impedance.

Energising the CAPTAP system, by opening the earth-switch in Figure 3.11, the transient voltage from the shield-wire will have a DC-charge on it. This is due to the fact that the voltage across the source capacitance is at its peak when the current is interrupted at its zero crossing.

3.4.3.2 Overhead Shield-wire Voltage

The voltage on the overhead shield-wire tends to increase with an increase in load current (see Figure 3.8, Figure 3.9 and Figure 3.10). This is due to the high Q-factor of the circuit, which is close to perfect resonance and has no damping. The shield-wire on the prototype substation was protected against these high voltages in three ways (see Figure 3.12):

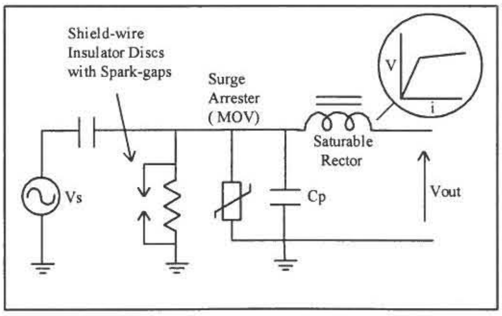


Figure 3.12 : Shield-wire Voltage Protection

- Spark gaps were installed on the insulators that isolate the overhead shield-wire from the 400kV line structure. These spark gaps will flash over if the overhead shield-wire voltage reaches 70kV rms.

- A gap-less metal oxide surge arrester was installed, between the shield-wire and the ground. The voltage will be clamped at the knee-point voltage of the arrester. With an increasing shield-wire voltage the arrester will conduct more and more in order to clamp the voltage, thus introducing more damping into the circuit. Due to the high source impedance and thus relative low fault currents, the distribution class surge arrester will not exceed its ratings.

- The saturation voltage of the reactor was specified to be just above its rated value. This causes the resonant circuit to go out of tune when the fault current exceeds the rated full load current of the reactor and thus limits the voltage that develops in the circuit.

3.4.4 COMPONENT SPECIFICATIONS AND OPERATIONS

3.4.4.1 Physical Capacitor

The value of the physical capacitor Cp in Figure 3.8 was determined as 120nF in paragraph 3.4.2.2. Three values of capacitances (63nF, 110nF and 150nF) were however chosen, which would provide a system output voltage of 22kV ± 2kV. The expected induced shield-wire voltage can then vary from 33kV to 60kV, assuming a source capacitance Cs of 104nF.

As described in paragraph 3.4.2.4, the voltage over the shield-wire increases to 39.8kV under full-load conditions. In practice, capacitors with a continuous voltage rating of 25kV were available. Two capacitors were connected in series to obtain a continuous voltage rating of 50kV.

3.4.4.2 The Reactor

An inductance of 45H ± 4%, with an internal resistance of 283Ω, was specified. This was based on the calculations in paragraph 3.4.2.3.

The current rating was specified at 2.3A for continuous operation, which would give the system an output capacity of 50kVA, assuming an output voltage of 21.7kV at full load. A short time (5 min.) overload current of 5A was specified as a precaution of potential fault conditions.

The voltage rating was specified based on the full load current rating in conjunction with the impedance value.

The saturation knee-point was desired at ±1.2 p.u. of the continuous rated current. This was specified in order to a characteristic of de-tuning the resonant circuit during fault conditions as described earlier.

3.4.4.3 Switch Gear

The switch gear for the system consists of a pole-mounted earthing switch and a manually operated line isolator (see Figure 3.11). Both switches are based on standard outdoor 22 kV switches, modified to 44 kV insulation levels.

The earthing switch is used to energise and de-energise the system and is activated using a pneumatic actuator, driven by a pressurised gas bottle and solenoid valves. The decision to use this gas-operated system was mainly due to the fact that a normal 44kV single-phase breaker costs approximately R 50 000-00, and its ratings are too high for this purpose. The closing time (time to de-energise) was specified at 0.5 seconds. When energising, the earth-switch breaks the capacitive short-circuit current of 1.5A by using a standard spring steel arcing contact which whip-lashes open. The earthing switch is remotely operated from the protection panel.

The line isolator is used to isolate the shield-wire source from the rest of the system, for maintenance purposes. The line isolator is manually operated by using a "link stick".

3.4.4.4 Current Transformers (CT's)

Due to the low current rating of the system, wound primary, class-X CTs were required. The CTs are required to measure the current flowing into the reactor and in the earthed return path. This allows over-current and earth-fault conditions to be detected. A turns ratio of 1 : 2.3 was specified with a maximum continuous primary current rating of 2.3 A.

3.4.4.5 Distribution Transformers

Three standard 22 kV : 230 V and 16 kVA distribution transformers were used. The transformers have 3 secondary tapings in order to select 95%, 100% or 105% turns ratios.

3.4.4.6 Transient Damping Filter

After it was discovered that the system needed a certain amount of damping for load switching and energising purposes, a filter was designed to dissipate any transient energy which may appear in the circuit. The type of filter is shown in Figure 3.13.

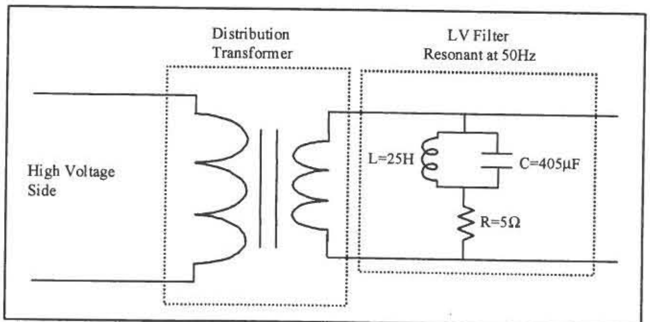


Figure 3.13 : Low-voltage Transient Filter for switching transients

With reference to paragraph 3.2.5, the band-pass filter was designed to provide a low impedance path for very high frequencies as well as for very low frequencies. The filter will however have a very high impedance at 50Hz, which is the frequency at which the filter was designed to resonate.

It was found through ATP simulations that better damping of the transient oscillations could be obtained using component values that provide higher energy storage capacity. Higher energy storage capacity components, however, are more expensive. The trade-off is in terms of cost versus performance. Components were chosen that are as small (energy storage) as possible, yet still providing satisfactory performance.

The resistor determines how quickly transient oscillations are damped. It was found during ATP simulations that optimum transient damping is achieved by a resistance of between 2.5 Ω and 10 Ω.

3.4.5 PROTECTION

There were five basic protection requirements which were considered to be important. A protection relay panel with a 12 V D.C. battery supply, using electro-mechanical relays, was used. The 12 V battery is charged by means of a standard trickle charger from the output of the system.

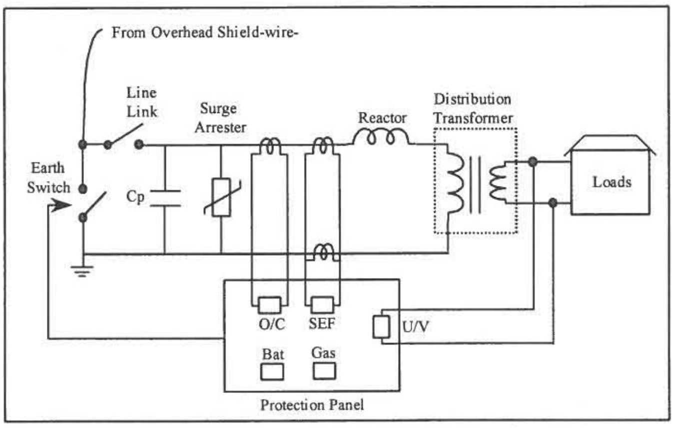


Figure 3.14 : Prototype CAPTAP Protection Scheme

3.4.5.1 Over Current (O/C)

The supply current is measured by means of a CT positioned on the source side of the reactor. The secondary side of the CT drives an instantaneous relay which was set at 2.5 A and causes the system to trip if the reactor current exceeds this value. This function protects the system in the case of short circuits on the output of the system.

3.4.5.2 *Sensitive Earth Fault (SEF)*

During a high resistance fault between the live output conductor and earth, somewhere on the distribution side of the system, the over-current relay may not detect the fault. It is thus necessary to have a means of discriminating between small loads and high resistance earth faults.

This can be done by measuring the current flowing into the reactor and the current returning from the load via the earthed return (neutral) conductor. The difference between these two currents is the earth fault current. In this way the earth fault relay can be set to be more sensitive (300 mA) than the over current relay.

3.4.5.3 *Under Voltage (U/V)*

If the insulated shield-wire is struck by lightning, the spark-gaps on the strain insulator assemblies (on the shield-wire) will flash over at 100 kV peak. There is the possibility that the 50 Hz induced voltage will sustain the arcs in these gaps after the lightning stroke has passed. This would render the system inactive, until the arcs were extinguished by some means. It was decided that this situation should be controlled, so that the system could not be left inactive for an indefinite period during such conditions. A relay is used to detect the output voltage (via the secondary of the distribution transformer) of the system. If the voltage drops below a pre-set value (200 V), the relay causes the system to trip by earthing the shield-wire. If the under voltage is a result of a spark-gap flash-over, the arcs will automatically be extinguished when the earth switch is closed. The relay re-opens the earth switch after a predetermined time (10 seconds) and thus re-energises the system.

- With the line link still in the open position and the earth-switch open, the induced shield-wire voltage were measured to be 45.1kV compared to the calculated value of 47.4 kV.

With reference to paragraph 3.4.2.1 the new source impedance can be determined as follows;

$$Zsource = \frac{Vs}{Isc} = \frac{45100\angle 0^\circ}{0.807\angle 90^\circ}$$

$$= 55886\angle -90^\circ = Xcs$$

$$\therefore \quad Xcs = \frac{1}{2\pi fCs} = 55886\Omega$$

$$Cs = 57nF$$

With this high source impedance the series resonant circuit will be out of tune, and the output voltage will be too low. The calculated value of Cs was 104nF.

3.4.6.2 System Output Voltage

Due to the higher shield-wire source impedance, the output voltage had to be reduced so that the total (including the physical capacitor) capacitive source impedance (magnitude) could still be close to that of the reactor.

The next lower standard Eskom voltage was 11kV and with reference to paragraph 3.4.2.2 and formula (3.5) the following:

$$Vcp = Vs * \left(\frac{Xcp}{Xcs + Xcp} \right)$$

$$\therefore Vcp = Vs * \left(\frac{Cs}{Cs + Cp} \right)$$

$$\therefore Cp = \left(\frac{Vs * Cs}{Vcp}\right) - Cs$$

$$= \left(\frac{45100 * 57nF}{11000}\right) - 57nF$$

$$= 177nF$$

An 11kV output voltage will thus require a physical capacitor of 177nF, but the only available capacitances were (63nF, 110nF and 150nF). With a 150nF capacitor, the output voltage is expected to be as follows (see formula (3.5)):

$$Vcp = Vs * \left(\frac{Cs}{Cs + Cp}\right)$$

$$Vcp = 45100 * \left(\frac{57}{57 + 150}\right)$$

$$Vcp = 12.41kV$$

The output voltage is expected to be 12.41kV, which is close enough, due to the fact that the distribution transformers can still tap ± 5%.

To determine whether the circuit is tuned or not, the resonance frequency can be determined (see Figure 3.8, Figure 3.9 and formula (3.1)).

For resonance Xct = Xl

$$Xct = \frac{1}{2\pi fCt} = 15377\Omega$$

$$Xl = 2\pi fl = 13823\Omega$$

$$Fo = \frac{1}{2\pi\sqrt{LCt}}$$

$$Fo = \frac{1}{2\pi\sqrt{44H * 207nF}}$$

$$= 52.74Hz$$

3.5 SUMMARY

Chapter Three described a number of basic concepts, which will be referred to further through this thesis, i.e. electromagnetic and electrostatic coupling, ferro-resonance and series and parallel resonance. This chapter also provided an overview of the design, erection and the problems experienced while the Prototype CAPTAP substation was built.

Chapter Four will provide a step-by-step design guide from which a CAPTAP substation can be designed and erected. The Component Value Spreadsheet is described in detail, in order to use standardised component values and series compensation for future CAPTAP substation designs. By using the Component Value Spreadsheet, a CAPTAP system with a natural resonant frequency of 50Hz can be obtained.

Central University of Technology, Free State

CHAPTER FOUR

CAPTAP DESIGN AND CONSTRUCTION GUIDE

4.1 INTRODUCTION

Chapter Three described a number of basic concepts, which will be referred to further through this thesis, i.e. electromagnetic and electrostatic coupling, ferro-resonance and series and parallel resonance. The chapter also provided an overview of the design, erection and the problems experienced while the Prototype CAPTAP substation was built.

Chapter Four will provide a step-by-step design guide in order to design and build a CAPTAP substation. The Component Value Spreadsheet is described in detail, in order to use standardised component values and series compensation for future CAPTAP substation designs. By using the Component Value Spreadsheet, a CAPTAP system with a natural resonant frequency of 50Hz can be obtained.

Practical experience gained by the first ever field CAPTAP project lead to a more compact method, using tables and calculations to design and construct a CAPTAP substation.

Computer simulations were essential during the initial design of the CAPTAP technology. This design guide will not involve in-depth computer simulations that require specially trained personnel. In future, network planners and project engineers will be able to design and build a CAPTAP substation by making use of this design guide.

4.2 REQUIREMENTS FOR A CAPTAP SUBSTATION

In order justify the building of a CAPTAP substation, the following conditions must be adhered to:

- A 400kV transmission line must be situated in the vicinity of the proposed supply point (the more distant the customers are, the more expensive the project will be).

- No alternative permanent form of supply, such as rural lines or conventional substations, which will provide a more cost-effective supply, must be located in the vicinity of the CAPTAP substation.

- The customers must be of domestic nature (farmers or small communities), and not be mining or industrial loads.

- Free access to the site must be available in order to keep the initial cost as low as possible (no need to build an access road).

- The customers must be aware of the cost implication and be properly quoted by Eskom's customers services. A feasible study must be conducted and the customers must accept Eskom's terms and conditions before the project can commence. The designer must bear in mind that the customer might be required to re-wire his premises, depending on the present standard of his wiring.

4.3 LONG LEAD-TIME COMPONENTS

The following standardised equipment must be ordered as soon as the project is technically and economically approved (see Appendix H):

- 44kV Single-phase Earth-switch (Triswitch from Linegear 2000, with trimotor actuator)

- 44kV Single-phase Line Link

- Series Reactor with three taps (40, 45 and 50 Henry)

- Capacitor Bank (see Appendix B)

- 44kV Distribution class MOV Surge arrester

- 44kV Protection current transformers (CT)

- Special neutral current transformer (CT)

- Protection panel manufactured as per design in Appendix E, with 24V battery and battery charger.

The above mentioned equipment must be insulated for 44kV, due to the high voltage over the Reactor and the total capacitance during full-load conditions.

The distribution transformer and the customer supply-point equipment can only be ordered once the system voltage is determined.

4.4 EARTH ELECTRODE

The actual design of the CAPTAP substation can begin once a proper site has been obtained. A proper earth electrode for the substation is essential, and will be the initial construction phase.

The soil resistivity of the selected site must be measured and the earth electrode designed according to Eskom Distribution Standard, Part 2, Earthing [3] (see Appendix C).

In order to obtain an even better earth electrode resistance to true earth, the earth electrode can be connected to the 400kV tower's earth. This can result in an earth electrode resistance to true earth with a value less than one ohm.

4.5 EARTH-SWITCH

The earth-switch must be installed, as described in Chapter Four, after the installation of the earth electrode. At this stage no protection panel or remote control box is required to operate the earth-switch. It can be operated by means of a link stick.

The earth-switch must be installed on a pole 9m above ground level, and properly connected to the earth electrode mentioned above (see Appendix D).

4.6 LINE INSULATION

Arrange a 400kV live-line working team to insulate the overhead shield-wire from the towers as this will not require outages on the Extra-high Voltage lines. These lines play a significant role in the Eskom network. The live-line team must be informed that their assistance will be required for at least two days, depending on the tower configuration and the terrain.

The live-line team must insulate one of the overhead shield-wires for approximately 10km. The shield-wire must be insulated by means of 44kV post or long-rod insulators, depending on the type of 400kV structure. The shield-wire must also be inline insulated at the ends of the 10km section. It must be carefully noted that the more of the shield-wire that gets insulated, the more power will flow into the remaining earthed points.

The proposed shield-wire to be insulated must be earthed to the general mass of earth through the earth-switch, before the live-line team can commence with the insulation. It is suggested that the live-line team begin insulating at the CAPTAP substation. Only one overhead shield-wire must be insulated. The live-line team can now insulate the 10km section of shield-wire, knowing that it will be earthed at all times. Additional earth-tails can be added to ensure a safe working environment.

Once the 10km section of shield-wire is fully insulated, the live-line workers must be cleared from the towers while the earth-switch is still in the closed position, connected to ground.

4.7 SOURCE PARAMETERS

With the earth-switch in the closed position and all the additional safety earth tails removed, measure the short-circuit current Isc by simply connecting a "clip-on" current meter onto the earth-tail that comes from the earth-switch and goes into the ground via the earth electrode (see Figure 4.1).

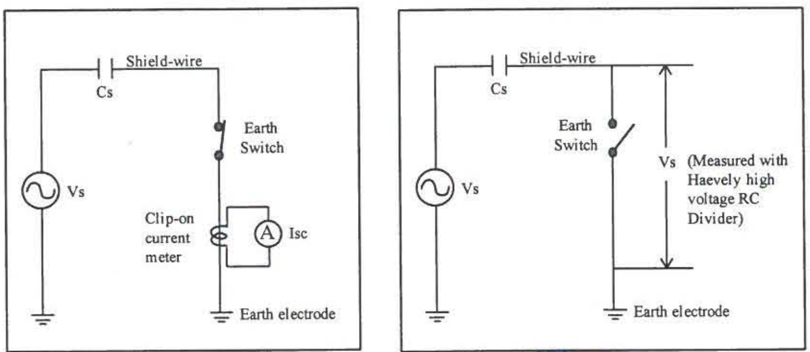


Figure 4.1 : Source Parameters

At this stage, the complete installation must be regarded as live and current carrying. By opening the earth-switch, the insulated earth-wire voltage will now rise to its full potential.

Measure the open-circuit shield-wire voltage, that is the source voltage Vs, across the earth-switch, between the shield-wire and the earth electrode. A "Haefely high-voltage RC divider", of Eskom Technology Research and Investigations mobile measuring facility, is required to measure a voltage of this magnitude (see Figure 4.1).

The true source parameters of this shield-wire source are now properly measured, and not calculated by computer simulations, where a magnitude of variables exist as experienced by the author with the field project.

4.8 SYSTEM COMPONENT VALUES

In Figure 4.2 the value of the physical capacitor Cp for the voltage divider and the value of L for the series compensation must still be determined.

To explain the rest of this step-by-step method, an example will be used.

Assuming that the measured values for Isc and Vs are as follows:

Isc = 1.3 A and Vs = 40kV

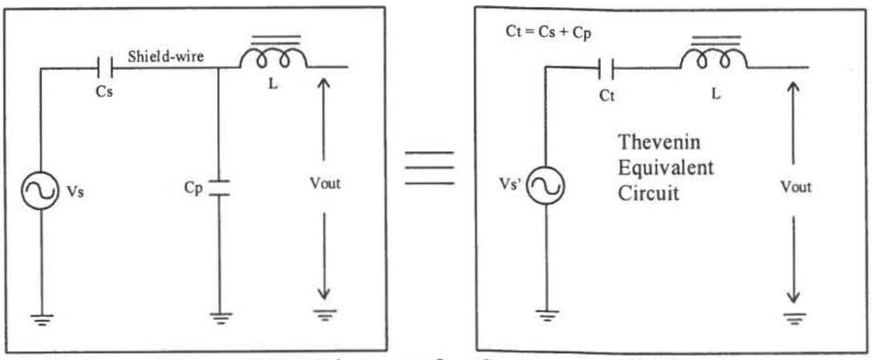


Figure 4.2 : Diagram for Component Values

The designer must bear in mind that the source voltage will remain virtually constant, independent of whether the insulated section is lengthened or shortened .

4.8.1 PURPOSE OF THE COMPONENT VALUE SPREADSHEET

The spreadsheet in Table 4.1 is designed to calculate the exact length of shield-wire to be insulated, taking the following into consideration:

- The source capacitance Cs and the physical capacitor Cp must form a voltage divider and produce a standard output voltage, e.g. 11 or 22kV.
- The physical capacitor has twelve different configurations, as shown in Appendix B.
- The lower the system output voltage, the lower the resultant output power will be.
- The system must be tuned at 50Hz, the inductive reactance of the reactor Xl must be equal to the capacitive reactance of the combination of the source capacitor Cs plus the physical capacitor Cp.

Insert the source values into Table 4.1 to obtain the corresponding results.

Table 4.1 : Component Value Spreadsheet

Inputs		Outputs					
Vs(kV) =	40.00	**Cp(nF)**	**Csn**	**Vs'(kV)**	**ℓ(km)**	**P(kW)**	**Fo(Hz)**
Isc(A) =	1.30	63.5	161.7	28.72	15.627	66.05	50.00
L(H) =	45.00	80.5	144.7	25.70	13.983	59.11	50.00
ℓ(km) =	10.00	89	136.2	24.19	13.162	55.63	50.00
f(Hz) =	50.00	93	132.2	23.48	12.775	54.00	50.00
		102	**123.2**	**21.88**	**11.905**	**50.32**	**50.00**
Calculate		110	115.2	20.46	11.132	47.05	50.00
Xcs(ohm) =	30769.23	112	113.2	20.10	10.938	46.24	50.00
Cs(nF) =	103.45	150	75.2	13.35	7.265	30.71	50.00
Cs(nF/km) =	10.35	155	70.2	12.46	6.782	28.67	50.00
XL(ohm) =	14137.17	**161**	**64.2**	**11.40**	**6.202**	**26.22**	**50.00**
Ct(nF) =	225.16	178	47.2	8.38	4.559	19.27	50.00
w =	314.16	190	35.2	6.25	3.399	14.37	50.00

4.8.2 EXPLANATION OF THE COMPONENT VALUE SPREADSHEET

Valuable field experience obtained by the author from the first field CAPTAP substation lead to the compilation of these formulae and the spreadsheet. <u>The designer must use the formulae in this section to create a Component Value Spreadsheet.</u>

The two main components of the system are the physical capacitor Cp and the reactor L. This design tends to standardise on a physical capacitor as shown in Appendix B, and a standard reactor value with three taps (40,45 and 50 Henry).

From the Component Value Spreadsheet the designer can only alter the values in the input section. The source voltage Vs and the short-circuit current Isc are measured values as explained in paragraph 4.7. The reactor is one of the standardised components, having three standard selectable values L, of which one is selected. The length of the insulated shield-wire is denoted by ℓ and the system frequency by f.

Below are the formula required to obtain the values in the calculated section. These values are a function of the output section:

- $w = 2.\pi.f = 314.16$
- The source impedance $Xcs = \dfrac{Vs}{Isc} = Zsource$,
- the source capacitance $Cs = \dfrac{1}{w.Xcs}$
- the source capacitance per kilometre $Cs(nF/km) = \dfrac{Cs}{km}$
- the total capacitance for resonance $XL = w.L = Xct \qquad Ct = \dfrac{1}{w.Xct}$

The output values are calculated as follows:

- Cp = Twelve different configurations of the physical capacitor (see Appendix B)
- the Source capacitance that is needed Csn = Ct – Cp
- the output voltage $Vs' = Vs * \left(\dfrac{Csn}{Csn + Cp}\right)$
- Length of line to be insulated ℓ = Csn * Cs/km

- The estimated output power available P = Vs' * 2.3(reactor full-load current)

- Natural resonant frequency $Fo = \dfrac{1}{2\pi\sqrt{L.(Cp + Csn)}}$ (this is the frequency at which the CAPTAP system will resonate and not the system frequency)

4.8.3 ANALYSING THE COMPONENT VALUE SPREADSHEET

The source parameters Vs and Isc will remain the same until the exact length of shield-wire to be insulated, is determined.

The reactor value is the only value at this stage that may be altered between its three tapings (40, 45 and 50 Henry).

In Table 4.1 a reactor value L of 45 Henry was inserted. The designer can now search for a standard output voltage Vs', that is close to either 11kV or 22kV, in the Vs' column. From Table 4.1, it becomes evident that in order to obtain an output voltage Vs' of 11.40kV, with a 45 Henry reactor, a physical capacitor Cp of 161nF is required and the insulated shield-wire must be shortened to 6.202km. To obtain an output voltage Vs' of 21.88kV, with a 45 Henry reactor, a physical capacitor Cp of 102nF is required and the insulated shield wire must be lengthened to 11.905km.

In reality the exact lengths of 6.202km and 11.905km would not be possible, due to the span-lengths of approximately 350 meters between the 400kV structures.

By altering the value of Csn, the output voltage Vs' can be adjusted. This will however increase or decrease the length of insulated shield-wire required, as well as the natural resonance frequency of the system, thus de-tuning the system. The natural resonant frequency must always tend to be as close as possible to 50Hz. Table 4.2 shows Csn adjusted to 130.3nF, to provide an output voltage Vs' of 22.41kV, and thus lengthen the shield-wire to 12.566km. This voltage is more acceptable for a 22kV system.

Table 4.2 : Component Value Spreadsheet

Inputs	
Vs(kV) =	40.00
Isc(A) =	1.30
L(H) =	45.00
ℓ(km) =	10.00
f(Hz) =	50.00
Calculate	
Xcs(ohm) =	30769.23
Cs(nF) =	103.45
Cs(nF/km) =	10.35
XL(ohm) =	14137.17
Ct(nF) =	225.16
w =	314.16

Outputs					
Cp(nF)	Csn	Vs'(kV)	ℓ(km)	P(kW)	Fo(Hz)
63.5	161.7	28.72	15.627	66.05	50.00
80.5	144.7	25.70	13.983	59.11	50.00
89	136.2	24.19	13.162	55.63	50.00
93	132.2	23.48	12.775	54.00	50.00
102	**130.0**	**22.41**	**12.566**	**51.55**	**49.26**
110	115.2	20.46	11.132	47.05	50.00
112	113.2	20.10	10.938	46.24	50.00
150	75.2	13.35	7.265	30.71	50.00
155	70.2	12.46	6.782	28.67	50.00
161	64.2	11.40	6.202	26.22	50.00
178	47.2	8.38	4.559	19.27	50.00
190	35.2	6.25	3.399	14.37	50.00

By altering the value of Csn the natural resonant frequency will shift from 50Hz to 49.26Hz, which is still acceptable. The author suggests that the natural resonant frequency of the system may not shift more than 1Hz due to the uncertainty of the effect of a de-tuned system.

Table 4.3 : Component Value Spreadsheet

Inputs	
Vs(kV) =	40.00
Isc(A) =	1.30
L(H) =	50.00
ℓ(km) =	10.00
f(Hz) =	50.00
Calculate	
Xcs(ohm) =	30769.23
Cs(nF) =	103.45
Cs(nF/km) =	10.35
XL(ohm) =	15707.96
Ct(nF) =	202.64
w =	314.16

Outputs					
Cp(nF)	Csn	Vs'(kV)	ℓ(km)	P(kW)	Fo(Hz)
63.5	139.1	27.47	13.450	63.17	50.00
80.5	122.1	24.11	11.807	55.45	50.00
89	**113.6**	**22.43**	**10.985**	**51.59**	**50.00**
93	109.6	21.64	10.599	49.78	50.00
102	100.6	19.87	9.729	45.69	50.00
110	92.6	18.29	8.955	42.06	50.00
112	90.6	17.89	8.762	41.15	50.00
150	52.6	10.39	5.089	23.90	50.00
155	47.6	9.40	4.605	21.63	50.00
161	41.6	8.22	4.025	18.91	50.00
178	24.6	4.86	2.382	11.19	50.00
190	12.6	2.50	1.222	5.74	50.00

Reset the formulas in the Csn column and change the reactor value to 50 Henry (one of the three tap settings). From Table 4.3 it is evident that an output voltage Vs' can be obtained using a physical capacitor Cp of 89nF and a 10.985km section of insulated shield-wire. By using a 50 Henry reactor an acceptable output voltage Vs' can be obtained, without shifting the natural resonant frequency and thus de-tuning the system.

4.8.4 EVALUATION OF THE COMPONENT VALUE SPREADSHEET

An acceptable output voltage can be obtained, by using the standardised reactor L (with its three settings) and the physical capacitor Cp (with its twelve configurations), in conjunction with the Component Value Spreadsheet. By using the Component Value Spreadsheet to its full potential, the system will have a natural resonant frequency at 50Hz, with the required output voltage.

4.9 COMPLETION OF THE CAPTAP SUBSTATION

At this stage an exact length of shield-wire is calculated for the measured source values of Isc and Vs. The earth-switch can now be closed and then secured by adding removable earth-tails from the shield-wire side of the earth-switch to the earth electrode. The live-line team can now undertake their final adjustment to the insulated shield-wire, according to the result from the Component Value Spreadsheet. Once this is done the assistance of the live-line team is no longer required.

With the new source capacitance Csn the short-circuit current Isc can be calculated:

$$Isc = \frac{Vs}{Xcsn}$$

$$= \frac{40000}{\left(\dfrac{1}{w.Csn}\right)}$$

$$= 1.43\,A$$

The short-circuit current Isc can again be measured as in paragraph 4.7 and then be compared with the calculation of the Component Value Spreadsheet. This should prove the Component Value Spreadsheet compiled by the author.

The remaining of the CAPTAP substation can now be constructed as shown in the drawings in Appendix D. For the protection drawings and cable diagrams refer to Appendix E.

After the construction of the substation is completed, the single-phase rural line can be connected to the substation.

4.10 PRE-COMMISSIONING OF CAPTAP SUBSTATION

The protection must be checked and the settings confirmed. The 24V backup battery must be fully charged. Once everything have been checked, all the temporarily earth-tails must be removed. The line link must be closed and then the earth-switch can be opened, using the remote control switch in the protection panel, in order to energise the system. The system is now energised and the output voltage on the secondary side of the auxiliary transformer can be measured.

To calculate the voltage regulation, the voltage between no-load and full-load must be measured.

To test whether the Sensitive Earth Fault (SEF) protection is working, a short-circuit can be applied between the neutral conductor and ground.

To test for O/C discrepancy between the customer and the CAPTAP substation, a short-circuit must be applied between the live and neutral wires on the customer LV side. This must trip the customer's LV breaker and not the CAPTAP substation.

After all pre-commissioning tests are completed, the CAPTAP substation must be isolated and earthed (see Appendix G).

4.11 COMMISSIONING OF THE CAPTAP SYSTEM

At this stage the earth-switch is still in the closed position with the line link in the open position (see Figure 5.1). The rural line link to the customers must be in the open position and the CAPTAP substation must be earthed properly.

To energise the CAPTAP system the exact procedures in Appendix G must be followed.

4.12 SUMMARY

Chapter Four provided a step-by-step design guide from which a CAPTAP substation can be designed and erected. The Component Value Spreadsheet is described in detail, in order to use standardised component values and series compensation for future CAPTAP substation designs. By using the Component Value Spreadsheet, a CAPTAP system with a natural resonant frequency of 50Hz can be obtained.

Chapter Five will describe the methods, problems and design alterations experienced by the author, while building the Pilot CAPTAP substation. The Component Value Spreadsheet from Chapter Four will be applied and the requirements for a tuned CAPTAP system will be determined.

CHAPTER FIVE

IMPLEMENTATION AT CUSTOMER SITE

5.1 INTRODUCTION

Chapter Four provided a step-by-step design guide from which a CAPTAP substation can be designed and erected. The Component Value Spreadsheet is described in detail, in order to use standardised component values and series compensation for future CAPTAP substation designs. By using the Component Value Spreadsheet, a CAPTAP system with a natural resonant frequency of 50Hz can be obtained.

Chapter Five will describe the methods, problems and design alterations experienced by the author, while building the Pilot CAPTAP substation. The Component Value Spreadsheet from Chapter Four will be applied and the requirements for a tuned CAPTAP system will be determined.

There was a serious need to construct a CAPTAP substation in a sparsely populated area after the prototype built by Leigh Stubbs of Eskom Transmission Department in 1992. Unfortunately the Prototype CAPTAP was not situated close to any domestic customers who have not yet experienced the benefit of electricity.

Eskom management agreed to subsidise a Pilot CAPTAP substation, on condition that the cost be kept as low as possible. The author took the initiative to design and construct a proper low-cost substation in an area which justifies this kind of technology. It was decided that the equipment from the prototype substation would be re-used in order to build a Pilot CAPTAP substation.

Figure 5.1 shows the general layout of the Pilot CAPTAP substation and the customer supply points.

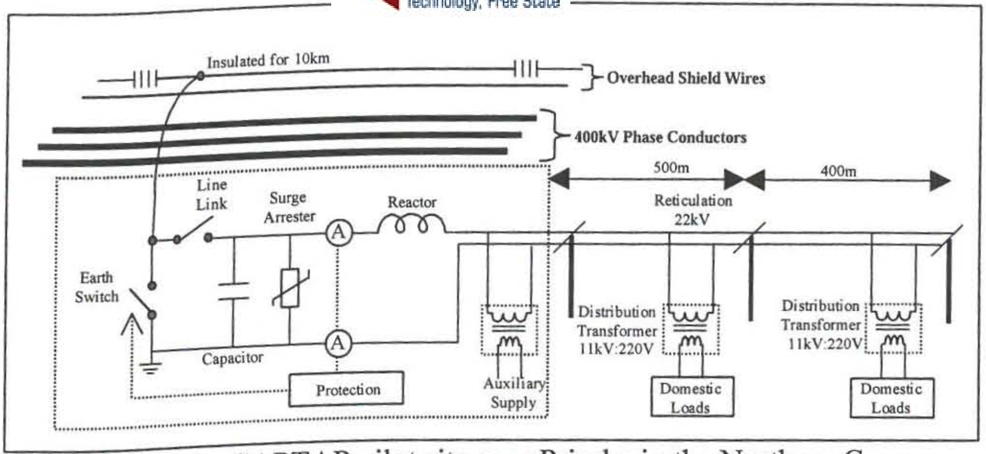


Figure 5.1 : CAPTAP pilot site near Prieska in the Northern Cape

5.1.1 SITE SELECTION

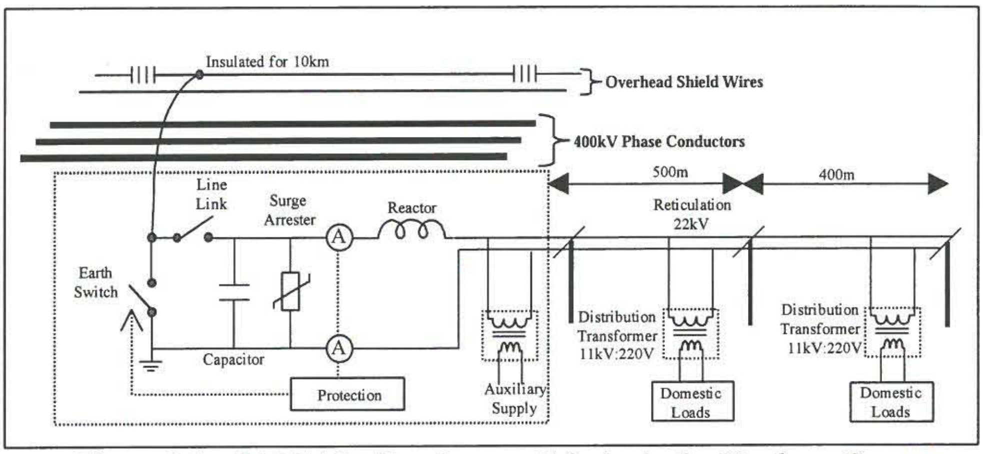
The main criteria for a pilot site in order to erect a proper low-cost CAPTAP substation, are the following:

- A 400kV transmission line must be in close proximity to the proposed site, typically a kilometer or two.
- No rural lines must be located in the vicinity of the pilot site, from which power can be supplied to the customers.
- The area must have a low-density population.
- The customers must be of a domestic nature (farmers or small communities), and no mining or industrial customers.

In order to meet the above-mentioned criterion in South Africa, the most obvious area to focus on would be the Northern Cape region which is sparsely populated and where a large number of Extra-high Voltage lines cross the region.

The author contacted a number of Eskom Field Service Centres in the Northern Cape area. The Prieska Field Service Centre appeared to be the most willing to participate.

Mr Peet Van Schalkwyk, the Customer Services Manager in Prieska, together with the author, drove through the Prieska region and visited a number of



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Mr Peet Van Schalkwyk, the Customer Services Manager in Prieska, together with the author, drove through the Prieska region and visited a number of customers situated close to the 400kV lines in the area. Seven possible Pilot CAPTAP sites were identified, of which one eventually was selected.

The selected site consists of two farming households, the one 500m and the other 900m from the 400kV Hydra-Kronos line (see Figure 5.1).

5.1.2 CUSTOMERS

The customers are Mr A Hugo on the farm Poortjie No. 1 and Mr K Prins on the farm Poortjie No. 2. Both of the above farmers had no access to any electricity other than their 5kW diesel generators and battery supplies, the nearest Eskom rural line being approximately 42km away. An 11kV or 22kV rural line of this length would cost approximately R3 million, and due to these costs could not be financially justified. Both of the premises had to be rewired due to the sub-standard wiring of their electrical installations. None of these installations complied to SABS 0142 wiring of premises. The earth electrode installations of the premises were improved as well.

The basic appliances used by these customers are: Electric kettles, stoves, flat-irons, washing-machines, sound equipment, micro-wave ovens, fridges, freezers, lights, heaters, toasters, small induction motor water pumps, welding plants, etc.

The customers were more than willing to re-wire their premises in order to obtain the benefit of a permanent supply of electricity.

5.2 COMPUTER SIMULATIONS AND CALCULATIONS

In-depth computer simulations were performed on the Apollo Domain 4000 workstation, using the Alternative Transients Program (ATP). See Appendix A for details on the 400kV and 22kV line dimensions, and specifications on the remainder of the equipment used for the simulations.

5.2.1 SOURCE PARAMETERS

With reference to the theory in Chapter Three, the computer simulation results were as follows (see Figure 5.2):

Vs = 31.4kV

Isc = 0.669A (Short-circuit the tap-off shield-wire to ground)

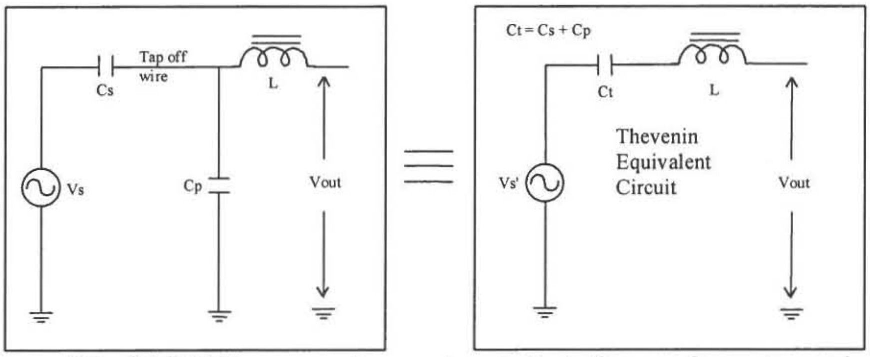

Figure 5.2 : CAPTAP source values and equivalent diagram for system values

The Component Value Spreadsheet as described in Chapter Five (CAPTAP Design Guide) paragraph 4.8 will now be used to determine the length of shield-wire to be insulated. By inserting the Source values, Reactor inductance and the initial insulated length of line, into Table 5.1, the output values are calculated:

Table 5.1 : Component Value Spreadsheet

Inputs	
Vs(kV) =	31.40
Isc(A) =	0.67
L(H) =	44.00
ℓ(km) =	10.00
f(Hz) =	50.00

Calculate	
Xcs(ohm) =	46935.72
Cs(nF) =	67.82
Cs(nF/km) =	6.78
XL(ohm) =	13823.01
Ct(nF) =	230.28
w =	314.16

Outputs					
Cp(nF)	**Csn**	**Vs'(kV)**	**ℓ(km)**	**P(kW)**	**Fo(Hz)**
63.5	166.8	22.74	24.592	52.30	50.00
80.5	149.8	20.42	22.085	46.97	50.00
89	141.3	19.26	20.831	44.31	50.00
93	137.3	18.72	20.242	43.05	50.00
102	128.3	17.49	18.915	40.23	50.00
110	120.3	16.40	17.735	37.72	50.00
112	118.3	16.13	17.440	37.09	50.00
150	**80.3**	**10.95**	**11.837**	**25.18**	**50.00**
155	75.3	10.26	11.100	23.61	50.00
161	69.3	9.45	10.215	21.73	50.00
178	52.3	7.13	7.708	16.39	50.00
190	40.3	5.49	5.939	12.63	50.00

The reactor and the physical capacitor Cp values are fixed, because these components had to be re-used from the prototype substation. The reactor value is 44 Henry and the capacitor value can be connected to obtain twelve different values. This can occur as long as there are two or more capacitor cans in series, to accommodate the insulation levels (see Appendix B).

From the above calculations it can be seen that in order to obtain an 11kV output voltage, the designed voltage, a physical capacitor of 150nF will be required. This will provide a calculated output voltage of 10.95kV and an expected maximum power output of 25.18kW, with a section of 11.84km of insulated shield-wire.

5.3 SUBSTATION CONSTRUCTION AND SITE ESTABLISHMENT

The author who designed the substation was the project leader, and was a member of the construction team on the pilot CAPTAP project. This meant that he had to order the material, arrange the transport, co-ordinate the phasing of the project and be involved in the construction of the substation.

5.3.1 SUBSTATION CONSTRUCTION DESIGN

The Pilot CAPTAP substation was designed from scratch, for optimal savings and technology improvements, thus the term "low-cost substation".

The conventional substation with grid type earth-mat, yard stone and fencing proved too costly. A new low-cost design incorporating the latest technology and optimal savings were done by the author for this project. See Appendix D for detail drawings of the Pilot CAPTAP substation. This substation was designed to be 5m above ground level, on a wooden pole construction. The earth-switch, line link and physical capacitor Cp will be mounted on a single 9m wooden pole. The remaining equipment will be mounted on a four pole construction.

The protection and LV-Filter panels was mounted 1.5m above ground level at the bottom of the 9m poles. This was necessary in order to gain access to these panels.

The equipment inside the substation was wired with wolf conductor, due to the limitations on standard clamp sizes.

5.3.2 SITE ESTABLISHMENT

The author set up a camping site on Mr Prins' farm, from where he managed and co-ordinated the project. This was necessary in order to provide on-hand guidance and advice with the construction of the substation.

5.4 LINE ISOLATION

The 400kV Hydra-Kronos line was energised at the time the Pilot CAPTAP substation was erected. Due to the significance of this line in the Eskom network, the overhead shield-wire had to be insulated by a live-line working team. The live-line workers from Eskom in Cape Town climbed to 400kV structures, passing between the phase conductors while the line was still energised. They disconnected the overhead shield-wire at the predetermined structures and installed an insulator to insulate the shield-wire from the towers. At both ends of the section of insulated shield-wire, in-line insulators were installed.

No arcing horns were installed across the insulators on the insulated shield-wire, due to the fact that the Metal Oxide surge arrester in the Prototype substation clamped the over voltage before the arcing horns could flash over. This also reduces the cost of the CAPTAP substation.

The calculations in paragraph 5.2.1 indicated that the shield-wire must be insulated from the towers and the rest of the shield-wire for 11.84km. This was however not possible due to span-lengths of up to 360m. The actual distance of overhead shield-wire insulated was 12.246km.

5.5 EARTH ELECTRODES

For the CAPTAP substation a proper earth electrode with a low resistance to true earth is essential, because the earth electrode is used as a reference point.

The soil resistivity of the ground at the pilot site was initially measured by means of the Wenner method [3] (see Appendix C). By applying the Wenner method and using its tables and calculations, the earth electrode can be designed. The designed earth electrode for the pilot site was constructed as follows:

- Drill two, 150mm diameter, 20m deep, 10m apart, holes in the ground,
- install 2 x 10mm diam. x 20m copper rods in these holes,
- fill the holes with a special cement mixture,
- connect the tops of the two copper rods, with a 10mm copper rod, and connect this earth electrode to the CAPTAP substation.

The earth electrode resistance was measured, by using the method described in Appendix C, which resulted in a 5Ω resistance to true earth.

5.6 EARTH-SWITCH

In the prototype substation a pneumatic switch was used to energise and de-energise the CAPTAP substation. This gas operated switch did not operate properly, due to continuous gas leaks, and was therefore not reliable.

The author in conjunction with Linegear 2000 modified this gas operated switch into a proper low-cost 24V DC electrically operated switch. This single-phase tri-switch, as it is called by the manufacturer, is insulated for 44kV and can break a current of 400 Ampere. The tri-switch is driven by a tri-motor actuator. The tri-motor drive unit is connected to the tri-switch operating shaft by means of a linkage. The tri-switch is fitted with an arc-trap load-break chamber, which has a normal rating of 630 Ampere at 11kV and 200 Ampere at 22kV . The tri-switch can manually be operated by means of a link stick, which overrides the tri-motor drive.

5.7 ELECTROMAGNETIC AND ELECTROSTATIC COUPLING

Some field measurements taken by the author, while constructing the pilot CAPTAP project, explains the difference between electromagnetic and electrostatic coupling.

5.7.1 ELECTROMAGNETIC COUPLING

After the shield-wire insulators were installed, the shield-wire was still earthed at the one end. This was done for safety reasons before the shield-wire was actually coupled to the earth switch. After the shield-wire was connected to the earth switch, which was in the closed position, the shield-wire was earthed at two places. As shown in Figure 3.1, this formed a closed loop and thus electromagnetic coupling. A current of 8A was measured flowing through the earth–switch into ground. This high current was due to the electromagnetic coupling, where the induced current is directly proportional to the load current in the 400kV phase conductors.

5.7.2 ELECTROSTATIC COUPLING

The shield-wire was properly energised as a voltage source by disconnecting the last earthed point at the one end of the shield-wire. The shield-wire was now totally isolated from any part of the 400kV Hydra-Kronos line. At this stage the shield-wire was still earthed through the earth-switch at the substation. By energising the shield-wire as described above, the current through the earth-switch and thus into ground, dropped to 1.12A. The current dropped, due to the electrostatic coupling, between the 400kV phase conductors and the insulated overhead shield-wire that was taking place (see Figure 3.2).

5.8 SOURCE PARAMETERS

5.8.1 SHORT-CIRCUIT CURRENT

The theoretical simulation, with Isc = 0.669A, differed from the measurements taken in the field as indicated in paragraph 5.7.2, where the short-circuit current Isc was measured 1.12A.

5.8.2 THE OPEN-CIRCUIT VOLTAGE

The pilot CAPTAP substation was successfully erected, with a distribution transformer as auxiliary supply, where the measurements was taken, and all the relevant equipment.

The substation was energised by closing the line link and opening the earth-switch (see Figure 5.1). The output voltage on the secondary side of the transformer measured in excess of 300V, thus driving the distribution transformer into s... kV/220V distribution transformer had to be replaced with ... nsformer. With the installation of the 22kV/220V transformer the secondary output voltage was 165V. When this voltage is transferred to the primary side of the transformer through the turns ratio of 95.65, the steady state voltage Vs' is 15.8kV (see Figure 5.3). The internal losses of the transformer were seen as negligible.

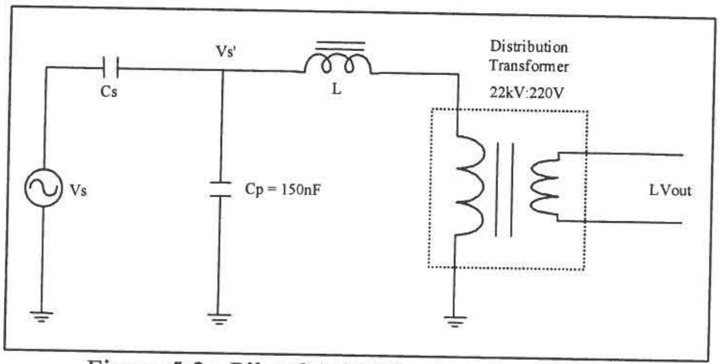

Figure 5.3 : Pilot CAPTAP substation Voltage

5.8.3 SOURCE IMPEDANCE AND SOURCE VOLTAGE

The total capacitance Ct, including the physical capacitor Cp, can now be calculated as follows:

$$Zct = \frac{Vs'}{Isc} = \frac{15800}{1.12} \qquad (5.1)$$

$$= 14107\Omega = Xct$$

$$Ct = \frac{1}{2\pi f Xct} = 225nF$$

From the above, and with the physical capacitor that is connected as 150nF, the source capacitance can be determined:

$$\text{Cs} = \text{Ct} - \text{Cp} \qquad (5.2)$$

$$= 225 - 150$$

$$= 75\text{nF}$$

The shield-wire voltage can now be determined:

$$Vs = Isc * Xcs \tag{5.3}$$

$$= 1.12 * \left(\frac{1}{2\pi f Cs} \right)$$

$$= 47.5\text{kV}$$

5.9 TUNING THE CAPTAP SYSTEM

For the CAPTAP system to be tuned, means that the system must have a natural resonant frequency of 50Hz, thus meaning that the capacitive reactance Xct must be equal to the inductive reactance XL of the circuit. Furthermore the source capacitance Cs and the physical capacitor Cp must form a voltage divider to provide one of the standard Eskom output voltages.

With the field measurements taken in paragraph 5.8.3, new source values had to be inserted into the Component Value Spreadsheet (see Table 5.2).

From Table 5.2 it is evident that, if a 8.53km of shield-wire was insulated, an output voltage of 10.78kV would have been obtained, with a physical capacitor of 178nF. This was however not possible, due to the fact that the live-line team had already left the site and could not return.

Table 5.2 : Component Value Spreadsheet

Inputs	
Vs(kV) =	47.50
Isc(A) =	1.12
L(H) =	44.00
ℓ(km) =	12.25
f(Hz) =	50.00

Calculate	
Xcs(ohm) =	42410.71
Cs(nF) =	75.05
Cs(nF/km) =	6.13
XL(ohm) =	13823.01
Ct(nF) =	230.28
w =	314.16

Outputs					
Cp(nF)	**Csn**	**Vs'(kV)**	**ℓ(km)**	**P(kW)**	**Fo(Hz)**
63.5	166.8	34.40	27.220	79.12	50.00
80.5	149.8	30.89	24.446	71.06	50.00
89	141.3	29.14	23.058	67.03	50.00
93	137.3	28.32	22.405	65.13	50.00
102	128.3	26.46	20.937	60.86	50.00
110	120.3	24.81	19.631	57.06	50.00
112	118.3	24.40	19.304	56.11	50.00
150	80.3	16.56	13.102	38.09	50.00
155	75.3	15.53	12.286	35.71	50.00
161	69.3	14.29	11.307	32.87	50.00
178	**52.3**	**10.78**	**8.532**	**24.80**	**50.00**
190	40.3	8.31	6.574	19.11	50.00

It was decided to alter the physical capacitor value to obtain the correct output voltage, although this would de-tune the system. From paragraph 3.4.6.2 and formula (3.5), the desired physical capacitance can be determined:

$$Cp = \left(\frac{Vs * Cs}{Vcp}\right) - Cs$$

$$= \left(\frac{47.5 * 75nF}{22}\right) - 75nF$$

$$= 86.9nF$$

The author decided to implement a 22kV system in the absence of a 249nF physical capacitor, which is required for an 11kV system, if 11kV is substituted in the above formula. A further reason was to rather have a more capacitive source than a more inductive source. Xc > Xl, due to loads as induction motors. A 22kV system provides better transfer capabilities for future expansions.

Thus, with a physical capacitor value of 89nF, obtained by adjusting the configurations, the expected output voltage Vcp would be (see formula (3.5)):

$$Vcp = Vs * \left(\frac{Cs}{Cs + Cp}\right)$$

$$Vcp = 47.5 * \left(\frac{75}{75 + 89}\right)$$

$$= 21.7\text{kV}$$

The 21.7kV output voltage would be adequate as the distribution transformer can tap ±5%. The resonance frequency of the pilot CAPTAP substation is as follows (see formula (3.1)):

$$Fo = \frac{1}{2\pi\sqrt{LCt}}$$

$$Fo = \frac{1}{2\pi\sqrt{44H * 164nF}}$$

$= 59.25\,Hz$

To tune the system perfectly, one of two methods can be used:

- As mentioned in paragraph 5.9, the insulated shield-wire can be shortened to 8.53km with Cp = 178nF, for an 11kV system or the shield-wire can be lengthened to approximately 18km for a 22kV system, with Cp = 112nF.
- If the 89nF capacitor is used, an additional reactor of 18 Henry must be coupled in series with the existing 44 Henry reactor to obtain a total reactance of 62 Henry.

5.10 FILTER ADAPTATION

The transient LV filter was designed for the prototype CAPTAP substation operating at a designed voltage of 110V (see Figure 3.13). An intermediate 220V/110V step-down transformer was installed, to accommodate the LV filter. The filter's impedance response versus frequency is shown in Figure 5.4.

The filter impedance was calculated for a number of different frequencies and a graph was plotted to show that the filter was appropriate for this purpose.

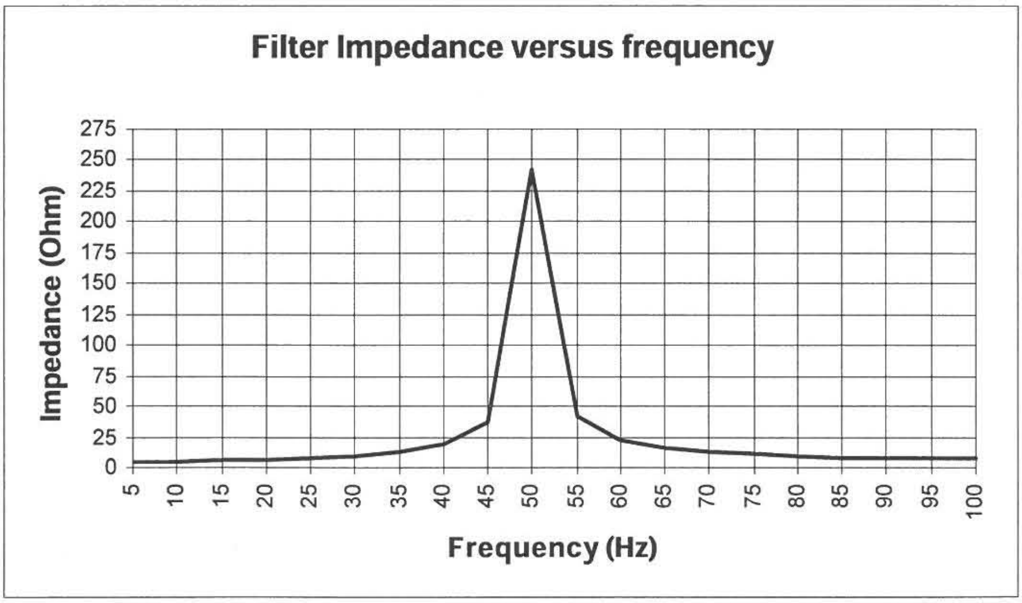

Figure 5.4 : CAPTAP LV Filter - Impedance versus Frequency curve

It is evedent from the graph that at 50Hz the filter has a very high impedance, and for any frequency higher or lower, the filter has a much lower impedance. The filter will thus dissipate any frequencies that do not coincide with 50Hz in the 5Ω resistor.

5.11 PROTECTION

The author, having a protection background, investigated the protection scheme and made some design modifications to the scheme. See Appendix E for detailed modified protection drawings.

The protection panel was designed to operate off a 12V battery, using a standard trickle charger from the output of the system. This however became a problem once the new 24V earth-switch was installed. At first the battery charger was altered to a 24V charger, with an additional converter to 12V because the protection panel operated on 12V. The two different voltages with their chargers were not feasible and the whole protection scheme had to be modified to operate on 24V only.

The author altered the original design, which required the installation of arching horns. The original idea was that once the arching horns flashed over, an under voltage situation would result, thus the under voltage protection was required. With no arching horns installed on the shield-wire insulators, no under voltage protection was required any more and was thus removed. The new earth-switch operated on its 24V tri-motor actuator, no gas protection was required and was also removed. With all these modifications the protection scheme was simplified even more (see Figure 5.5).

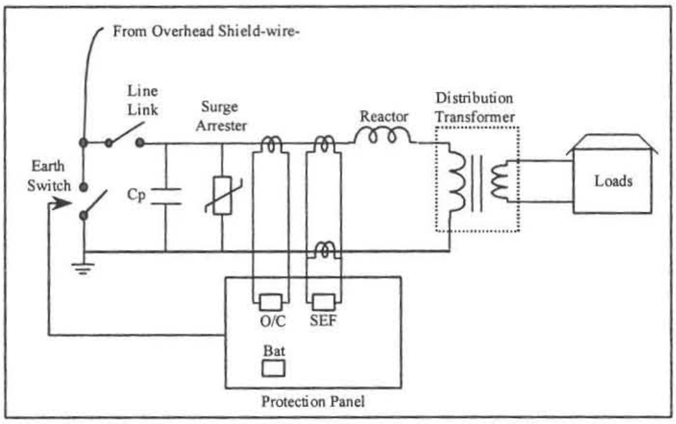

Figure 5.5 : Modified pilot CAPTAP protection scheme for the customer site

The over-current (O/C) and sensitive earth-fault (SEF) protections were delayed (for approximately one second) by timers. This was due to nuisance tripping while trying to energise the system.

5.12 RURAL 22KV SINGLE-PHASE LINE

A 900m 22kV single-phase Fox line was built to supply the two farmers at Poortjie No.1 and Poortjie No. 2

The line was constructed using a staggered vertical configuration, as this was the most cost-effective way (see Appendix A). The live conductor is at a potential of 22kV with respect to ground, and the neutral conductor was very close to ground potential, due to its construction (see Figure 5.1). A Single-wire Earth Return (SWER) line was considered, but due to the short length of line and the high cost of the earth electrodes, this was not viable. Another reason the SWER line was not considered was the fact that there would have been no sensitive earth-fault (SEF) protection on the substation or on the line.

5.13 CUSTOMER'S SUPPLY POINTS

The two customer supply points were erected as Eskom standard 22kV single-phase supply points. See Appendix F for detailed layout of a supply point and the earthing. Both customers had to re-wire their premises to accommodate the new supply.

5.14 PROBLEMS EXPERIENCED

5.14.1 ESKOM CONTROL CENTRE

Once the pilot CAPTAP substation was energised, confusion arose on how exactly this new substation operated. Eskom Control Centre in Kimberley required a step-by-step list of instructions on how to energise and de-energise the CAPTAP substation. It was the author's responsibility to create such a list (see Appendix G).

5.14.2 ENERGISING THE SYSTEM

While the system was energised, it sometimes tripped on O/C and SEF. This problem was investigated and solved by delaying the SEF and O/C trip times by means of inserting delay timers.

5.14.3 FRIDGES AND FREEZERS

The substation was energised and the actual testing could begin. All the usual house-hold equipment worked perfectly, with the exception of the fridges and freezers.

The type refrigerant equipment used on these two farms were unique. They were of the Low-temp and Minus 40 type. These refrigerant equipment fridges and freezers needed only to run for approximately 3 to 4 hours of a 24 hour cycle. During those short periods they freeze up properly to last for the rest of the 24 hour cycle. This kind of equipment was designed specifically for the farming community, who make use of generator plants. The generating plants usually run for 3 to 5 hours a night, at which time the fridges and freezers are "loaded" to last until the next evening. The fridges and freezers are equipped with a 700 to 800 Watt induction motor, in comparison to a more common house-hold fridge with a 200 to 300 Watt induction motor.

When starting or running one of these fridges or freezers, the lights started to flicker and the induction motor became very unstable. This seemed to be the ferro-resonance phenomena described in paragraph 3.2.3.

5.15 SUMMARY

Chapter Five described the methods, problems and design alterations experienced by the author, while building the Pilot CAPTAP substation. The Component Value Spreadsheet from Chapter Four was applied and the requirements for a tuned CAPTAP system were determined.

Chapter Six will describe some after commissioning experiments to prove the CAPTAP system.

CHAPTER SIX

AFTER COMMISSIONING EXPERIMENTS

6.1 INTRODUCTION

Chapter Five described the methods, problems and design alterations experienced by the author, while building the Pilot CAPTAP substation. The Component Value Spreadsheet from Chapter Four was applied and the requirements for a tuned CAPTAP system were determined.

Chapter Six will describe some after commissioning experiments to prove the CAPTAP system.

Initially the CAPTAP substation, the single-phase rural line and the customer supply points were commissioned, without the household supply being connected. The electrical equipment on the customers' premises were connected individually without any impact on the 220V, 50Hz, sinusoidal CAPTAP Voltage, except when the refrigeration equipment were connected.

6.2 EVALUATION CRITERIA

The CAPTAP system in this chapter will be evaluated by means of experiments. The hypothesis of the study will be tested. Further will the general protection on the system as well as normal load conditions be tested.

6.3 EXPERIMENT ONE: COMPONENT VALUE SPREADSHEET

6.3.1 PURPOSE

The purpose of this experiment is to prove that the Component Value Spreadsheet, with its standardised components, as described in Chapter Four is working. This experiment will also test the hypothesis of this dissertation.

6.3.2 METHOD

By using the pilot CAPTAP project as described in Chapter Five, the Component Value Spreadsheet can be proved. In Chapter four the author suggested that the standardised reactor must have a 40, 45 and 50 Henry tap-settings and the standardised physical capacitor must have twelve configurations as shown in Appendix B. For this experiment the 44 Henry reactor and the physical capacitor shown in Appendix B will be used. Both these components originated from the prototype CAPTAP substation and due to cost-implications, had to be re-used in the pilot CAPTAP substation.

With the standardised components and a fixed length of insulated shield-wire, the best configuration for the physical capacitor can be determined by using the Component Value Spreadsheet. The length of insulated shield-wire was fixed, due to the cost-implication for the live-line team to return to adjust the length.

The following steps will be conducted for this experiment (see Figure 5.1):

- Measure the short-circuit current Isc flowing through the earth-switch to ground, with the line link in the open position and the earth-switch in the close position.

- Due to the absence of a "Haefely high voltage RC divider", the source voltage Vs' must be determined by transferring the distribution transformer's LV voltage to the primary. In order to measure this voltage, the line link must be closed and the earth-switch opened.

- These source values must then be inserted into the Component Value Spreadsheet, in order to determine the best physical capacitor configuration to be used.

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- Due to the absence of a "Haefely high voltage RC divider", the source voltage Vs' must be determined by transferring the distribution transformer's LV voltage to the primary. In order to measure this voltage, the line link must be closed and the earth-switch opened.

- These source values must then be inserted into the Component Value Spreadsheet, in order to determine the best physical capacitor configuration to be used.

6.3.3 RESULTS

The short-circuit current Isc was measured 1.12A, flowing through the earth-switch, with the line link in the open position and the earth-switch in the close position.

The secondary output voltage of the 22kV/220V distribution transformer (in Figure 6.1) was 165V. When this voltage is transferred to the primary side of the transformer through the turns ratio of 95.65, the steady state voltage Vs' is 15.8kV. The internal losses of the transformer were seen as negligible.

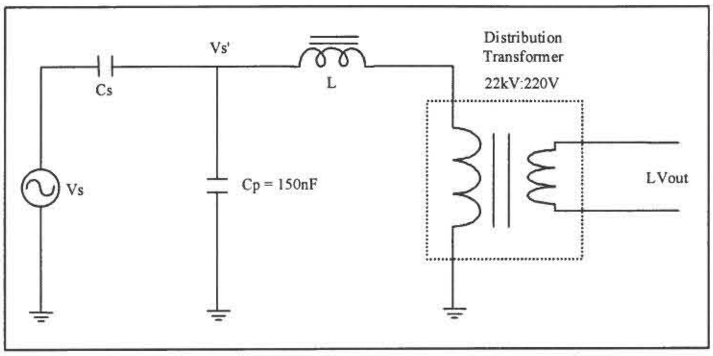


Figure 6.1 : Pilot CAPTAP substation Voltage

The total capacitance Ct, including the physical capacitor Cp, can now be calculated as follows (see Figure 4.2 and formula (3.3)):

$$Zct = \frac{Vs'}{Isc} = \frac{15800}{1.12}$$

$$= 14107\Omega = Xct$$

$$Ct = \frac{1}{2\pi f Xct} = 225nF$$

From the above, and with the physical capacitor that is connected as 150nF, the source capacitance can be determined (see formula (5.2)):

$$Cs = Ct - Cp$$

$$= 225 - 150$$

$$= 75nF$$

The shield-wire voltage can now be determined (see formula (5.3)):

$$Vs = Isc * Xcs$$

$$= 1.12 * \left(\frac{1}{2\pi f Cs} \right)$$

$$= 47.5\text{kV}$$

The source values Vs and Isc must be inserted into the Component Value Spreadsheet in Table 6.1.

Table 6.1 : Component Value Spreadsheet

Inputs	
Vs(kV) =	47.50
Isc(A) =	1.12
L(H) =	44.00
ℓ(km) =	12.25
f(Hz) =	50.00

Calculate	
Xcs(ohm) =	42410.71
Cs(nF) =	75.05
Cs(nF/km) =	6.13
XL(ohm) =	13823.01
Ct(nF) =	230.28
w =	314.16

Outputs					
Cp(nF)	**Csn**	**Vs'(kV)**	**ℓ(km)**	**P(kW)**	**Fo(Hz)**
63.5	166.8	34.40	27.220	79.12	50.00
80.5	149.8	30.89	24.446	71.06	50.00
89	141.3	29.14	23.058	67.03	50.00
93	137.3	28.32	22.405	65.13	50.00
102	128.3	26.46	20.937	60.86	50.00
110	120.3	24.81	19.631	57.06	50.00
112	118.3	24.40	19.304	56.11	50.00
150	**80.3**	**16.56**	**13.102**	**38.09**	**50.00**
155	75.3	15.53	12.286	35.71	50.00
161	69.3	14.29	11.307	32.87	50.00
178	52.3	10.78	8.532	24.80	50.00
190	40.3	8.31	6.574	19.11	50.00

From Table 6.1 it is evedent that for a physical capacitor Cp of 150nF, a source capacitance Csn of 80.3 is required for 50Hz natural resonance.

If the value of Csn in Table 6.2 is changed to 75.05nF, which is the true source capacitance Cs, the output voltage Vs' is exactly the same as it was measured.

Table 6.2 : Component Value Spreadsheet

Inputs	
Vs(kV) =	47.50
Isc(A) =	1.12
L(H) =	44.00
ℓ(km) =	12.25
f(Hz) =	50.00
Calculate	
Xcs(ohm) =	42410.71
Cs(nF) =	75.05
Cs(nF/km) =	6.13
XL(ohm) =	13823.01
Ct(nF) =	230.28
w =	314.16

Outputs					
Cp(nF)	**Csn**	**Vs'(kV)**	**ℓ(km)**	**P(kW)**	**Fo(Hz)**
63.5	166.8	34.40	27.220	79.12	50.00
80.5	149.8	30.89	24.446	71.06	50.00
89	141.3	29.14	23.058	67.03	50.00
93	137.3	28.32	22.405	65.13	50.00
102	128.3	26.46	20.937	60.86	50.00
110	120.3	24.81	19.631	57.06	50.00
112	118.3	24.40	19.304	56.11	50.00
150	**75.1**	**15.84**	**12.249**	**36.43**	**50.58**
155	75.3	15.53	12.286	35.71	50.00
161	69.3	14.29	11.307	32.87	50.00
178	52.3	10.78	8.532	24.80	50.00
190	40.3	8.31	6.574	19.11	50.00

This proves the Component Value Spreadsheet to be accurate, and does not provide a solution yet.

For a 22kV system voltage and by using formula (3.5) in paragraph 3.4.6.2 the desired physical capacitance can be determined:

$$Cp = \left(\frac{Vs * Cs}{Vcp}\right) - Cs$$

$$= \left(\frac{47.5 * 75nF}{22}\right) - 75nF$$

$$= 86.9nF$$

Thus, with a physical capacitor value of 89nF, obtained by adjusting the configurations, the expected output voltage Vcp would be (see formula (3.5)):

$$Vcp = Vs * \left(\frac{Cs}{Cs + Cp}\right)$$

$$Vcp = 47.5 * \left(\frac{75}{75 + 89}\right)$$

$$= 21.7\text{kV}$$

The 21.7kV output voltage would be adequate as the distribution transformer can tap ±5%. The resonance frequency of the pilot CAPTAP substation is as follows (see formula (3.1)):

$$Fo = \frac{1}{2\pi\sqrt{LCt}}$$

$$Fo = \frac{1}{2\pi\sqrt{44H * 164nF}}$$

$$= 59.25Hz$$

The pilot CAPTAP system is not tuned perfectly and will have a natural resonate frequency of 59Hz.

6.3.4 CONCLUSION

The Component Value Spreadsheet is accurate, but it is essential to be able to lengthen or shorten the insulated shield-wire while the live-line team is still on site. This is the main criteria for the Component Value Spreadsheet to be a proper working tool. With this new method of designing a CAPTAP system, cost will be reduced significantly, due to the fact that the adjustment of the standardised component values are basically cost-less and the minimum shield wire insulation will be required. The exact procedures to follow to obtain a low-cost and tuned CAPTAP system are described in Chapter Four.

6.4 EXPERIMENT TWO: CAPTAP PROTECTION

6.4.1 PURPOSE

The purpose of this experiment is to determine if the CAPTAP protection is working satisfactory.

6.4.2 METHOD

The system must be able to be energised and de-energised without any unnecessary protection tripping.

A neutral to earth fault must be applied on the 220V supply at the customers premises. This fault must only trip the customers earth-leakage protection, without tripping the CAPTAP substation.

A neutral to earth fault must be applied between the neutral conductor of the single-phase rural line and ground. This fault must trip the CAPTAP substation on Sensitive Earth Fault (SEF) protection.

A live to neutral fault must be applied on the customers 220V supply voltage, in order to prove the discrepancy between the customers over-current (O/C) protection and the CAPTAP O/C protection.

None of the above-mentioned tests should trip the CAPTAP substation, due to the protection on the customers premises.

6.4.3 RESULTS

Figure 6.2 shows the steady state system voltage. The system frequency is 50Hz and the voltage magnitude is approximately 220V (rms).

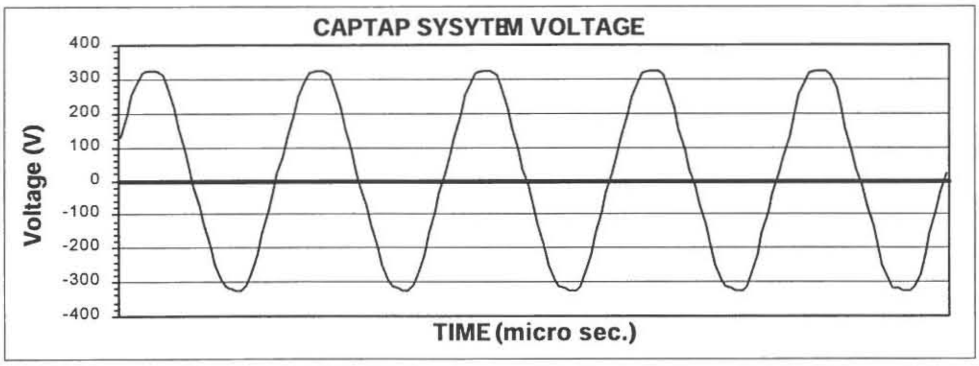


Figure 6.2 : CAPTAP 220V System Voltage, measured at customer site

By applying a neutral to earth fault on the customers 220V supply voltage, only the earth-leakage in the customers distribution box tripped. This prove that the earth-fault protection from the customers side is working.

A neutral to earth fault was applied between the neutral conductor of the single-phase rural line and ground. This fault tripped the CAPTAP substation and thus proving the Sensitive Earth Fault (SEF) protection.

Once the live to neutral fault was applied at the customers 220V supply voltage, the CAPTAP substation tripped on over-current and sensitive earth fault, which was not expected.

While the CAPTAP substation is energised, it sometimes tripped on over-current and Sensitive Earth Fault protection.

The trip operations occurred so quickly that the recordings were worthless.

The author installed timers on the protection circuits to be able to monitor the problems.

Figure 6.3 shows the voltage waveform that was obtained once a live to neutral fault has been applied.

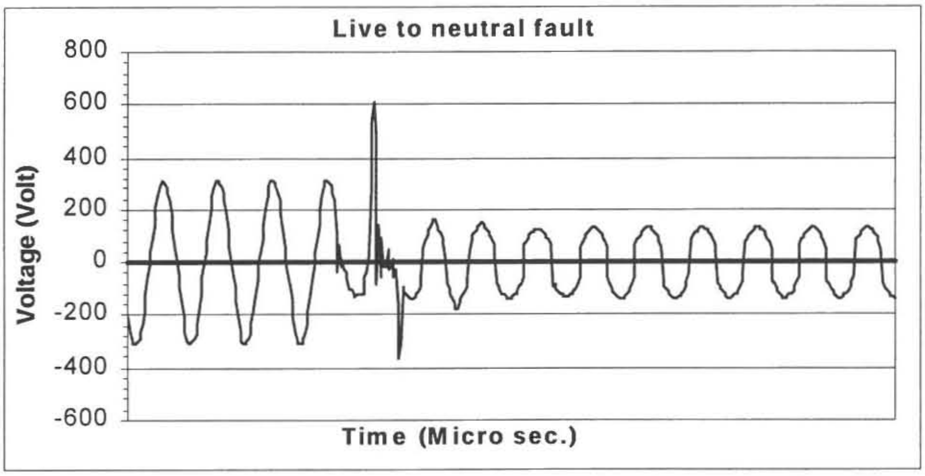


Figure 6.3 : CAPTAP voltage with live to neutral fault

The same waveform was recorded during the energising-trip (see Figure 6.4).

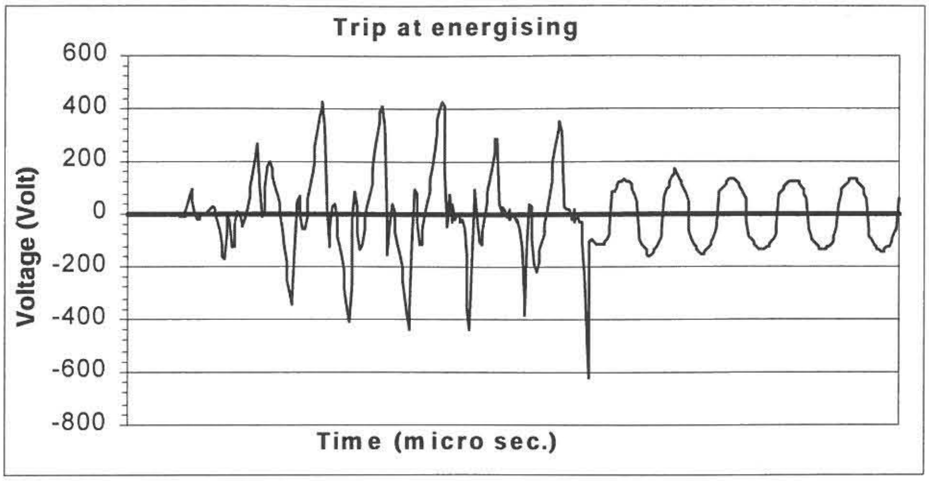


Figure 6.4 : CAPTAP voltage with trip at energising

At this stage the author realised that something was clamping the system voltage, once a fault occurred.

Simultaneous current measurements, during fault conditions, were taken in the protection circuits as well as in the earth-tails of the surge-arresters in the CAPTAP substation.

The surge-arrester on the live-conductor of the single-phase rural line, conduct every time that a live to neutral fault was applied.

6.4.4 CONCLUSION

With a live to neutral fault on the customers side, it causes a voltage rise across the reactor, due to its high impedance. The surge-arrester was rated for normal 22kV Eskom rural lines, which has a maximum continuous operating voltage (MCOV) of $22kV/\sqrt{(3)} = 12.7kV$. This explains why the surge-arrester has been conducting during fault conditions.

With energisasion the system transient voltages are very high and the surge arrester again conducted.

The surge-arresters were replaced with gap-arresters, with a maximum continuous operating voltage of 31kV and the protection was delayed by one second, to solve this problem.

6.5 EXPERIMENT THREE: REFRIGERATION EQUIPMENT

6.5.1 PURPOSE

The purpose of this experiment is to determine what causes the lights to flicker, once a fridge or a freezer is running from the 220V CAPTAP supply voltage.

6.5.2 METHOD

In order to investigate the effect that the fridge motor has on the CAPTAP supply voltage, the basic working of the fridge circuit must be studied.

The current and voltage waveforms must be recorded without any refrigeration equipment connected and with the fridge running from the 220V CAPTAP supply voltage. These recordings can be recorded by using a N-PTM Fault Recorder and a Dranetz recorder. These waveforms must be studied in an attempt to identify the problem. After the problem had been identified, a solution must be found in order to provide a suitable 220V supply.

6.5.3 BASIC WORKING OF FRIDGE CIRCUIT

Figure 6.5 schematically shows the basic electrical layout of these heavy-duty refrigerant equipment. The instant the induction motor is switched on, the current only flows in the running winding. The running winding's initial current is so high that the "pick up" coil immediately switched the starting winding in. The starting winding consists of a winding as well as a series capacitor, which provides a phase-shift for better starting. The starting winding will only stay in for a few moments. Once the induction motor reaches its running speed, the current through the running winding will drop below the "pick up" coil's setting and the starting winding will fall out.

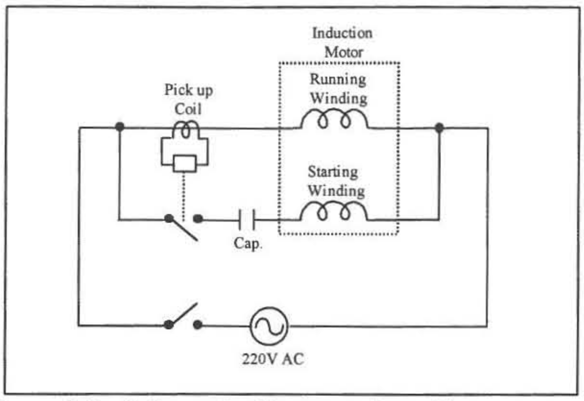


Figure 6.5 : Schematic diagram of a refrigerant motor

The running winding will now solely drive the induction motor. With a stable 220V source, the "pick up" coil will not switch the starting winding in again, unless the induction motor was shut down and restarted.

6.5.4 RESULTS

Figure 6.6 shows the 220V system voltage, without any refrigeration equipment connected.

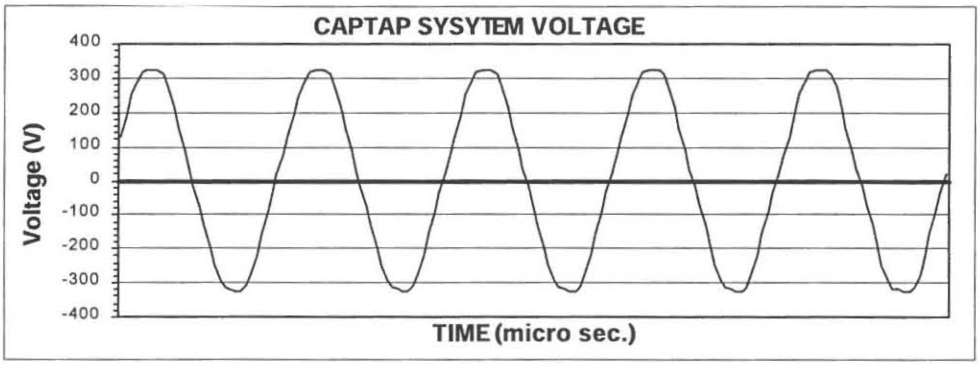


Figure 6.6 : 220V System Voltage, without refrigeration equipment

Although the system voltage waveform is not a perfect sinusoidal waveform, it is at 50Hz and the magnitude remains constant.

Figure 6.7 shows the voltage and current waveforms once the fridge is running. These waveforms are severely distorted. The voltage waveform, which is the larger one, appears to be modulated at approximately 17Hz. The current waveform is scaled by a factor of 10 in order to be visible on the same graph, and appears to have the same modulation present. The phase difference between these two waveforms appears to shift forwards and backwards all the time.

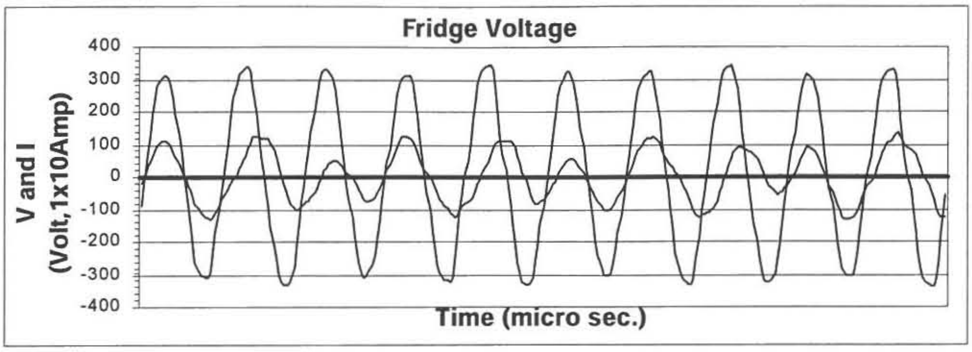


Figure 6.7 : 220V System Voltage, with fridge running

On the Dranetz recorder, the same phase-shift phenomenon was measured. This instrument also recorded the presence of the third harmonic, 8% on the current and 3% on the voltage were recorded.

While the fridge was running, the lights began to flicker due to the voltage modulation, thus indicating that the voltage amplitude changes all the time. The induction motor was running very unstable, and the "pick-up" coil was shuddering the contacts (closing and opening continuously) all the time.

This "pick-up" coil shuddering could in a sense explain the lights flickering and the voltage modulation. The running winding with the series capacitor switching in and out all the time could cause the phase angle to shift and the lights to flicker. The reason for the flickering lights can be justified in this way. What causes the "pick-up" coil to shudder, remains unanswered.

Unfortunately the problem is not that simple. Figure 6.8 shows the current and voltage waveforms with the "pick-up" coil bridged out.

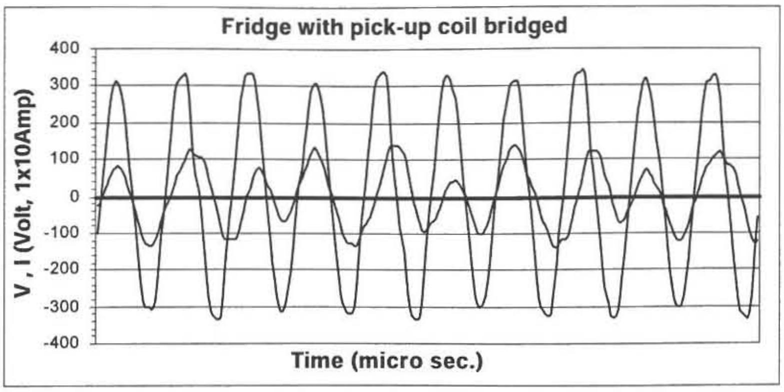


Figure 6.8 : Fridge waveforms with "pick-up" coil bridged out.

By short-circuiting the "pick-up" coil, the function of switching in the starting winding is disabled. This had no significant effect on the waveforms, thus proving the above-mentioned theory incorrect.

Due to the confusion at this stage, the fridge was connected to a 2.5kW generator, in order to see what the actual waveforms looks like (see Figure 6.9).

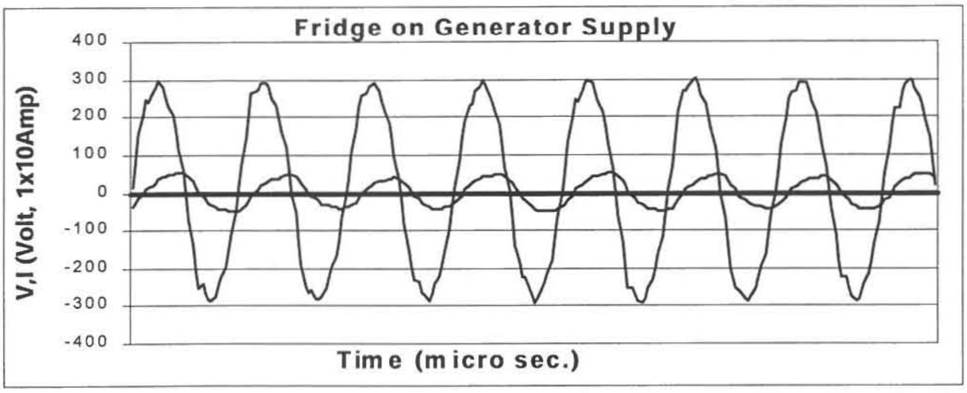


Figure 6.9 : Fridge waveforms with Generator supply

With the generator supply, non of the previous problems were experienced. No voltage or current modulation was visible and the phase difference remained constant. A 13% current and a 6.4% voltage deviation at the third harmonic frequency was measured.

Next, a normal household fridge was connected to the CAPTAP 220V supply voltage. There was no flickering of lights visible and thus no modulation or phase-shift were experienced. A 10% current and a 3% voltage deviation at the third harmonic frequency was measured.

In an attempt to temporarily solve the problems with the refrigeration equipment, the following experiment was conducted:

- An additional capacitor was connected, first in parallel and then in series.
- An additional inductor was connected, also first in parallel and then in series.

None of the above-mentioned experiments showed any improvement on the refrigerant equipment's waveforms.

Considering the ferro-resonance phenomenon as stated in paragraph 3.2.3, the author realised that the refrigeration circuit may need some sort of damping. After numerous tests and different configurations of adding resistance damping to the circuit, the author disclosed that a 5Ω, 500W resistor in series with the induction motor, as shown in Figure 6.10, neutralised the modulation and phase-shifting.

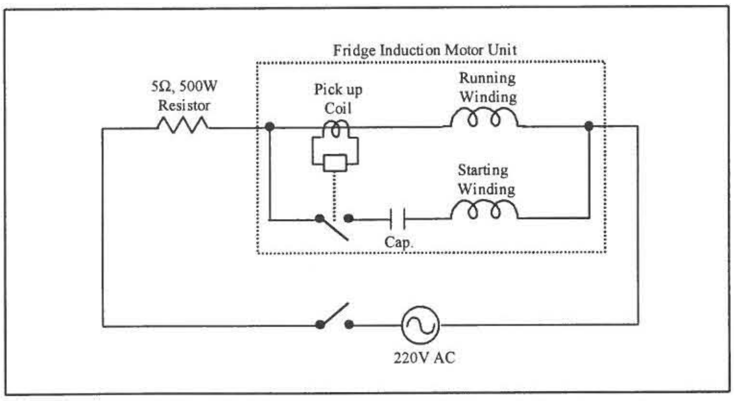


Figure 6.10 : Fridge motor with 5Ω resistor in series

The wattage of the resistor must be high due to the power dissipated ($P=I^2R$) in the resistor. The waveforms as shown in Figure 6.11 show no modulation on and no phase-shifting between the voltage and current waveforms.

The 5Ω, 500W resistor was mounted in a metal box with ventilation, and installed next to the induction motor of the fridge.

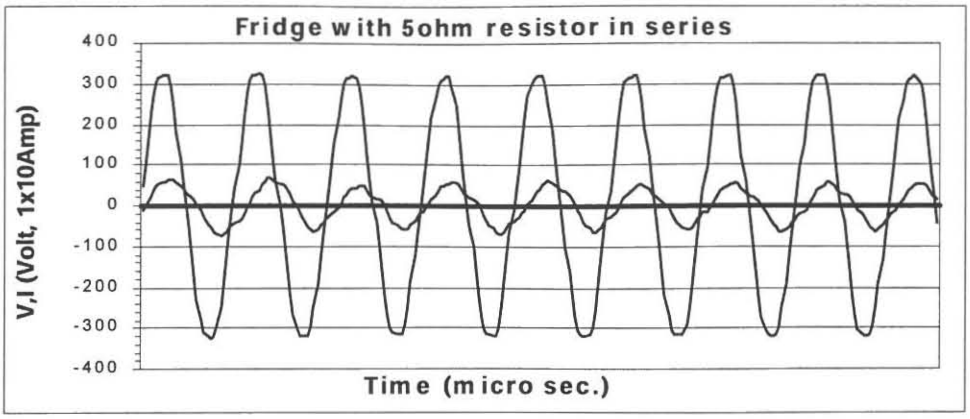


Figure 6.11 : Fridge motor with 5Ω resistor in series

6.5.5 CONCLUSION

This resistive damping indicates a temporary solution for the possible ferro-resonance phenomenon, or any other phenomenon that was present. The possibility that the natural resonant frequency, being 59Hz, could cause this phenomenon, must be investigated.

Unfortunately, once a second fridge or freezer (with a 5Ω resistor installed) was running at thc samc time, the modulation and the phase-shift phenomenon started all over again.

The only temporary solution was to equip all three of the freezers and the fridge with a 5Ω, 500 Watt resistor in series with their induction motors. This type of heavy-duty refrigerant equipment only requires four hours a day in order to "load" properly. Because two of the refrigerant equipment may not run at the same time, timers were installed on all four of them. Each unit was then set to run for a specific four hour period during the 24 hour cycle of a day. This is a temporary solution, which requires an in-depth investigation, that is beyond the scope of this thesis.

6.6 CONCLUSION OF EXPERIMENTS

The CAPTAP design guide, using the Component Value Spreadsheet and with standardised components, is working satisfactory.

The modified protection design solved the energising and live-to-neutral fault problems. This protection scheme can be the standard for all future CAPTAP systems.

Although the refrigeration problem was temporarily solved it still needs serious attention and must be investigated in the near future.

CHAPTER SEVEN

CONCLUSION AND FUTURE RESEARCH

7.1 CONCLUSION

7.1.1 COMPUTER SIMULATIONS

The design of the Prototype and Pilot CAPTAP substations were based on computer simulations. In both cases the computer simulations required were incorrect, to such an extent that the system output voltage had to be changed. This was due to the difficulty to simulate the conductor spacing with the varying tower height, due to the towers not on the same level. With the specifically designed length of insulated shield-wire (based on the simulations), the equipment had to be specified exactly. With the shield-wire already insulated when the project started, it would have been very costly to alter the insulated line length by recalling the live-line working team.

Neither the Prototype nor the Pilot CAPTAP substations were tuned perfectly. The Pilot CAPTAP system was worst off, with a natural resonant frequency of 59Hz.

The design method described in Chapter Five, does not make use of complex computer simulations, and promises to provide a 50Hz natural resonant frequency tuned system.

7.1.2 STANDARDISED COMPONENTS

In the past the three main constrains for designing and building a low-cost CAPTAP substation were:

- Highly skilled personnel with specific knowledge of the Alternative Transients Program (ATP) were required for simulations.

- For each new CAPTAP substation, new values for the physical capacitor and the reactor had to be determined. This proved to be inaccurate each time and worsen the chances for standardisation.

- The conventional method of building a CAPTAP substation with grid earth-mat, yard stone and fencing, adds significantly to the total cost of the substation.

By using this design guide as described in Chapter Five, the designer does not need to know the Alternative Transients Program (ATP), in order to be able to design a CAPTAP substation.

By using the above-mentioned design guide the designer can use standardised components for each CAPTAP substation in the future. Standardised components have the benefit of having to keep fewer strategic spares in the store for breakdowns. This new method can be used as an Eskom standard substation in the future.

In Appendix D a full set of drawings for a new low-cost pole-mounted substation is available for the designer. This new method of constructing a CAPTAP substation is environmental friendly, easy to use and costs much less than the previous methods.

7.1.3 COMPLYING TO HYPOTHESIS

This thesis complied to the hypothesis by providing an easy to use design guide for power tapping from Extra-high Voltage lines, using the insulated shield-wire and series compensation, <u>with standardised components</u>.

A further achievement was the cost savings that was incurred by:

- Designing and constructing a low-cost substation, with modified protection panel.

- Removal of the arcing horns.

7.2 RECOMMENDATION FOR FUTURE RESEARCH

The problems as discussed in Chapter Six, relating to the refrigeration equipment, require urgent attention.

Firstly the ferro-resonance phenomenon or the phenomenon that is causing the refrigerant equipment not to work with the CAPTAP supply voltage must be investigated.

The feasibility of using a Single-wire Earth Return (SWER) reticulation scheme in conjunction with this type of supply system can also be studied. This would improve the overall viability of implementing this type of scheme.

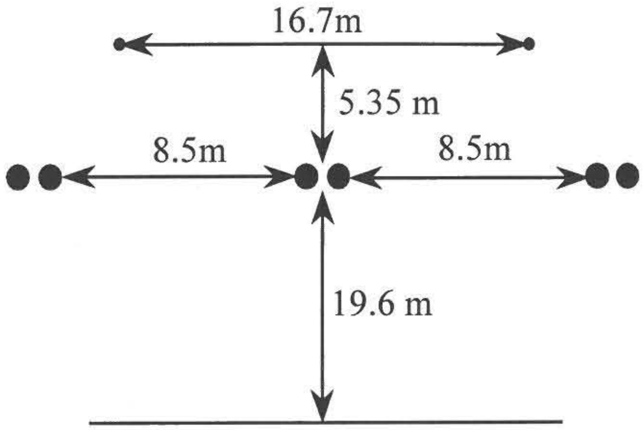
Appendix A : ATP Simulation Data

The data shown in this Appendix was used in the Alternative Transients Program (ATP), to simulate the Pilot CAPTAP substation. The simulations were necessary to pre-determine the length of overhead shield-wire to be insulated, in order to match the existing equipment recovered from the Prototype CAPTAP substation.

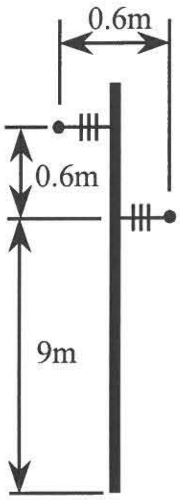
Data for ATP simulations

LV filter	
Inductor	X/R = 30
	L =25,25mH
	Knee point voltage 150V rms
Capacitor	400 µF 120V (3 sec. 240V)
Resistor	5Ω ,500W
Neutral CT	
Turns ratio	1/2.3
Class	X
Min. secondary knee point V	60V
Max. secondary magnetising I	120mA
Max. secondary resistance	1.0Ω
Max continuos current	2.5A
Short-time current	10A (3 sec.)
Reactor	
Cont. rated current	2.3A
Max. internal resistance	283Ω
Inductance	44H
Rated voltage	44kV (Phase to ground)
Saturation current	2.7A (rms)
Capacitor	
Capacitance	150nF
Continuous voltage	48kV
440kV line	
Type	517B
Conductor	Twin dinosaur 2/663
Earth wire	19/2.65
Conductor bundle	2/663
Conductor spacing	360
Continuos MVA	1147
Emergency MVA	1524
Length	188km
Pos/km	Zero/km
R = 0.003	R = 0.0342
X = 0.0364	X = 0.1302
B = 1.1152	B = 0.7396
22kV Line	
Conductor	Fox
Pos/km	Zero/km
R = 0.86	R = 0.95
X = 0.45	X = 1.76
B = 2.8	B = 1.46

400kV Conductor spacing

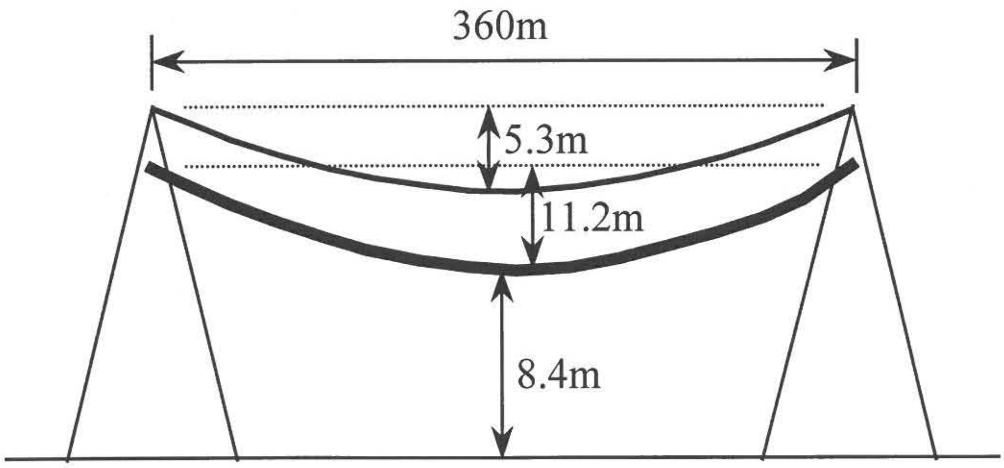


22kV Conductor-spacing



Span length = 120m
Sag = 1.5m

400kV Span length



Appendix B : Physical Capacitor Configurations

The capacitor bank from the Prototype CAPTAP substation was re-used in the Pilot CAPTAP substation, and its specifications is proposed to be the standard specifications for future CAPTAP substations. This Appendix shows the twelve different configurations this capacitor bank can be configured.

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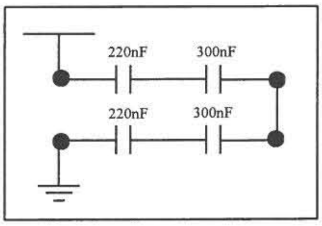
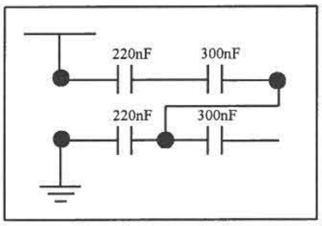
Physical Capacitor Couplings

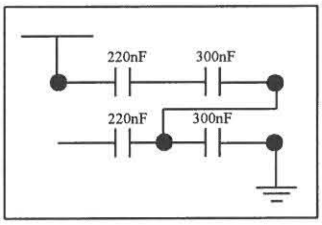
Ctotal = 63.5nF



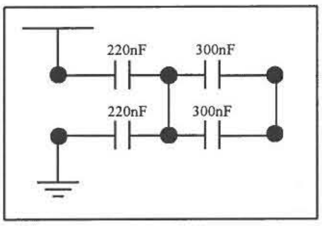
Ctotal = 80.5nF



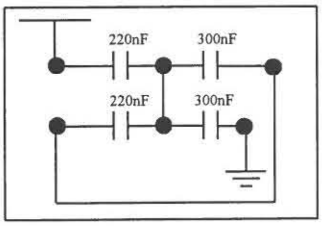
Ctotal = 89nF



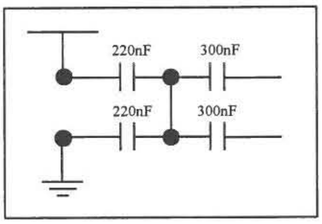
Ctotal = 93nF



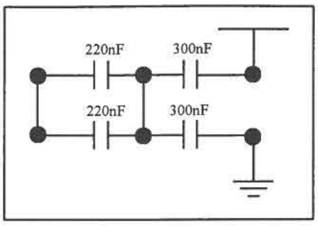
Ctotal = 102nF



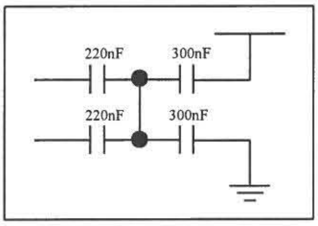
Ctotal = 110nF



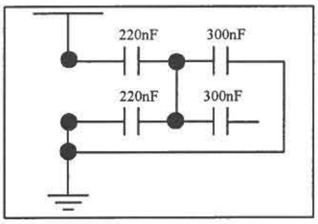
Ctotal = 112nF



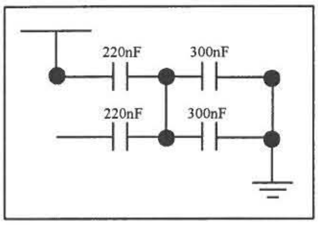
Ctotal = 150nF



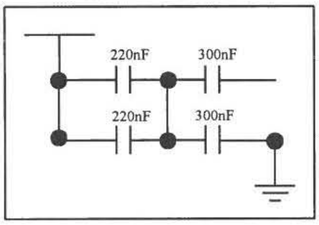
Ctotal = 155nF



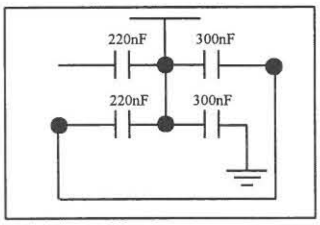
Ctotal = 161nF



Ctotal = 178nF



Ctotal = 190nF



Appendix C : Wenner Method of Measuring Soil Resistivity

The Wenner method showed in this Appendix was used to measured and determined the soil resistivity of the ground in the Pilot CAPTAP substation area. This Appendix also shows the method used to determined the earth electrode's resistance to true earth [3].

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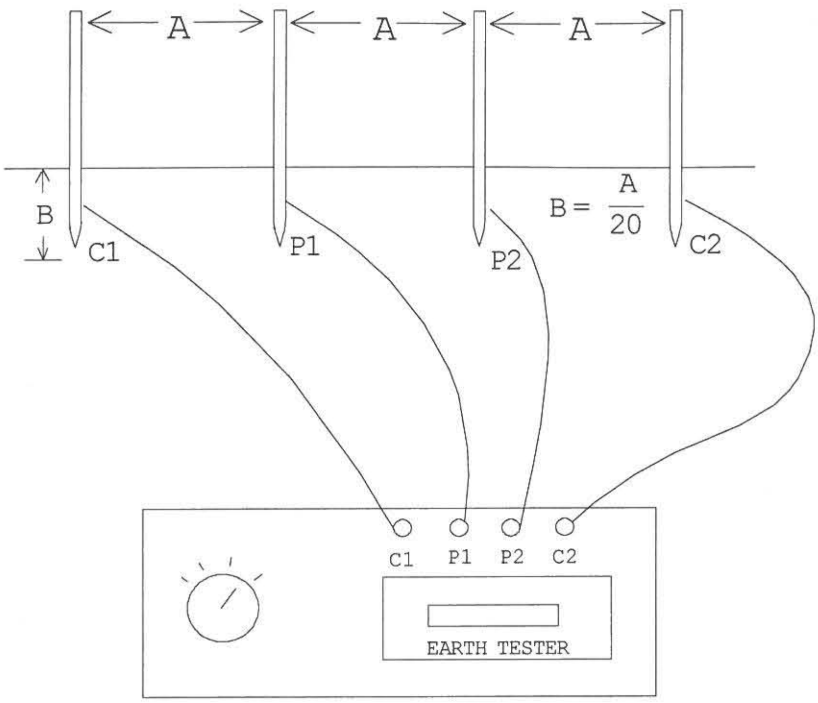
WENNER METHOD OF MEASURING SOIL RESISTIVITY

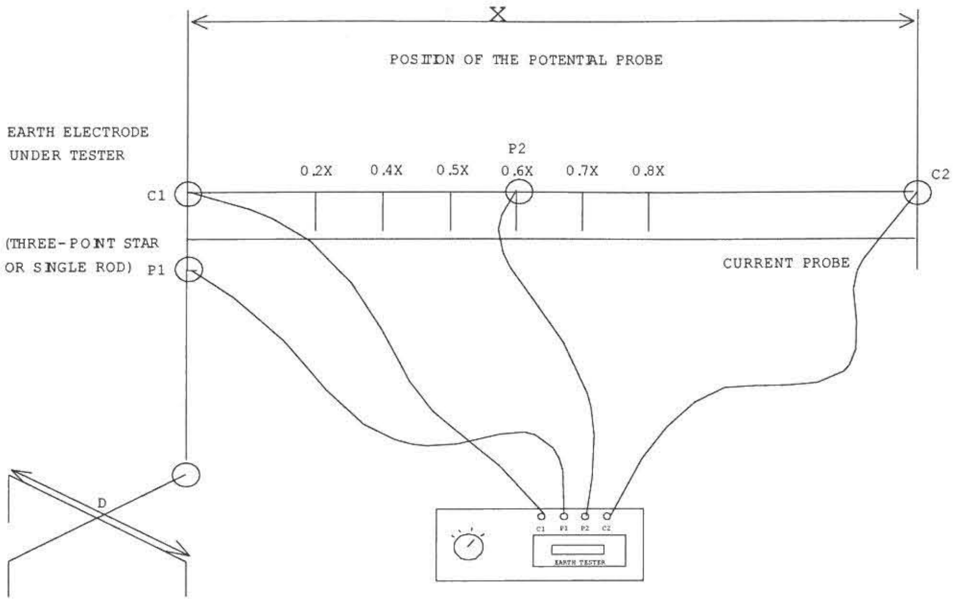


Four probes are driven into the earth along a straight line, at equal distances (A) apart, driven to a depth (B). The voltage between the two inner (potential) probes is then measured and divided by the current between the two outer current probes to give a value of mutual resistance (R). The resistivity is then:

If (B) is small compared to (A), as is the case of probes penetrating the ground for a short distance only, the equation is as follows: $\wp = 2\pi A R$

Where:	$\wp$	=	resistivity of soil in ohm metre
	R	=	resistance in ohms resulting from dividing the voltage between the potential probes by the current flowing between the current probes
	A	=	distance between adjacent probes in metre
	B	=	depth of the probes in metre

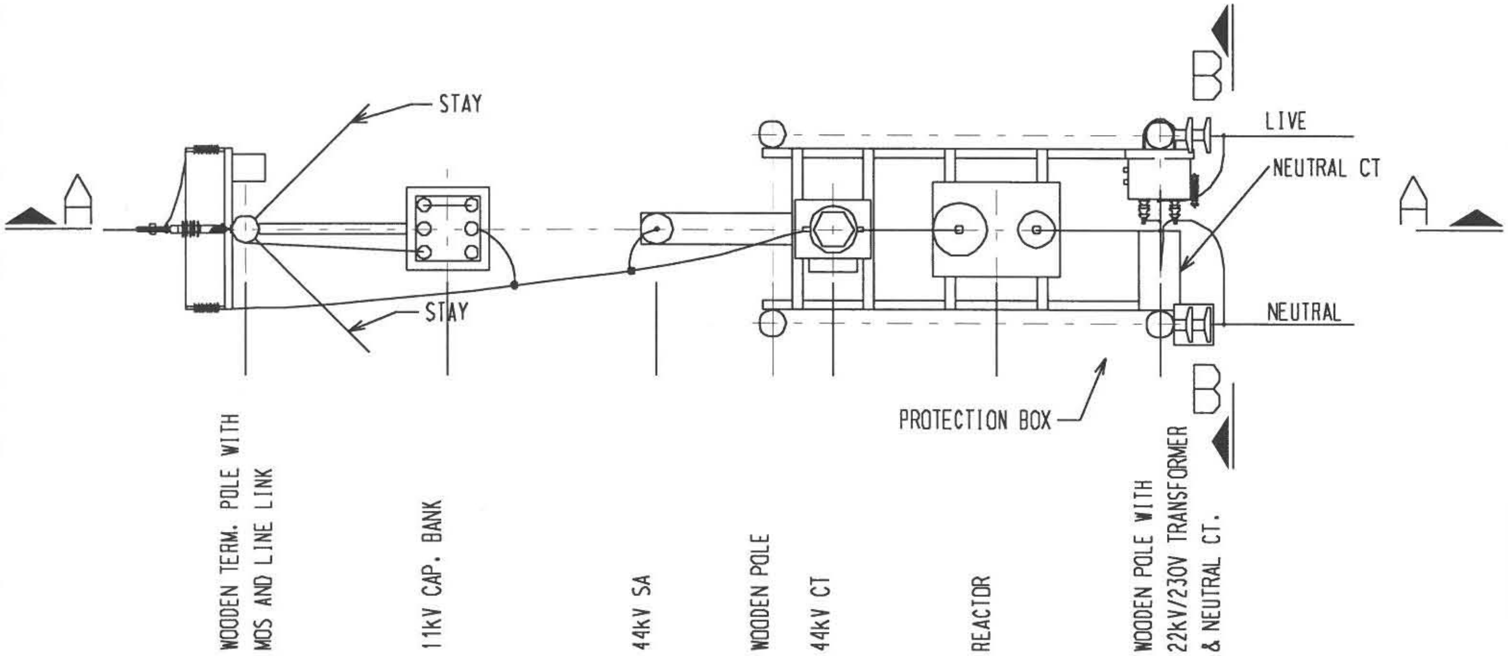
EARTH ELECTRODE RESISTANCE MEASUREMENT (61,8% METHOD)



The 61,8% method for measuring the resistance of an earth electrode is described in Eskom's Distribution Standard, Part 2, Earthing [3, p.25].

Appendix D : Pilot CAPTAP Substation Drawings

This substation drawings were drawn in the design phase of the Pilot CAPTAP substation and were modified with the building of the Pilot CAPTAP substation. The drawings are now Eskom standard drawings for future CAPTAP substations.



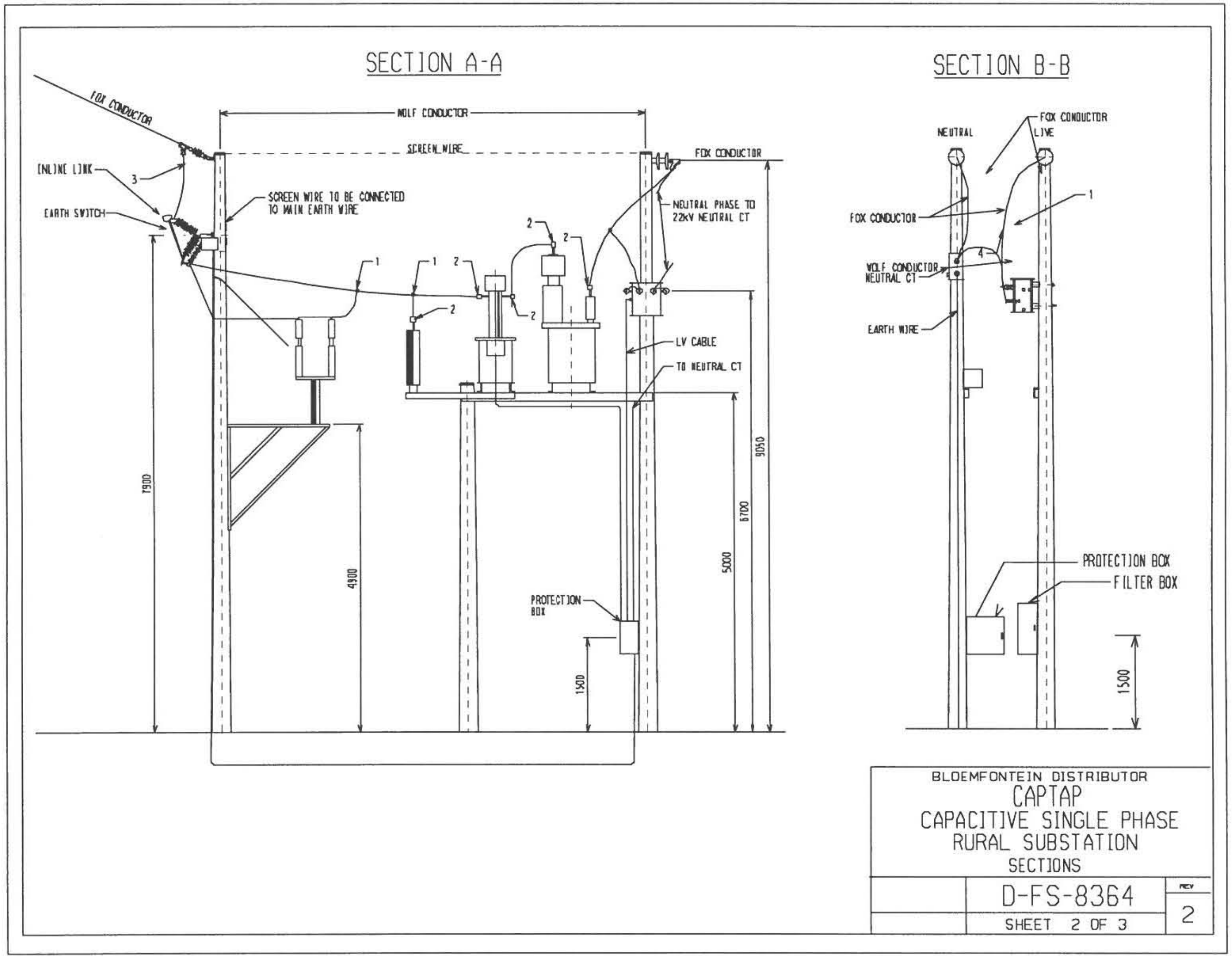
NOTES:

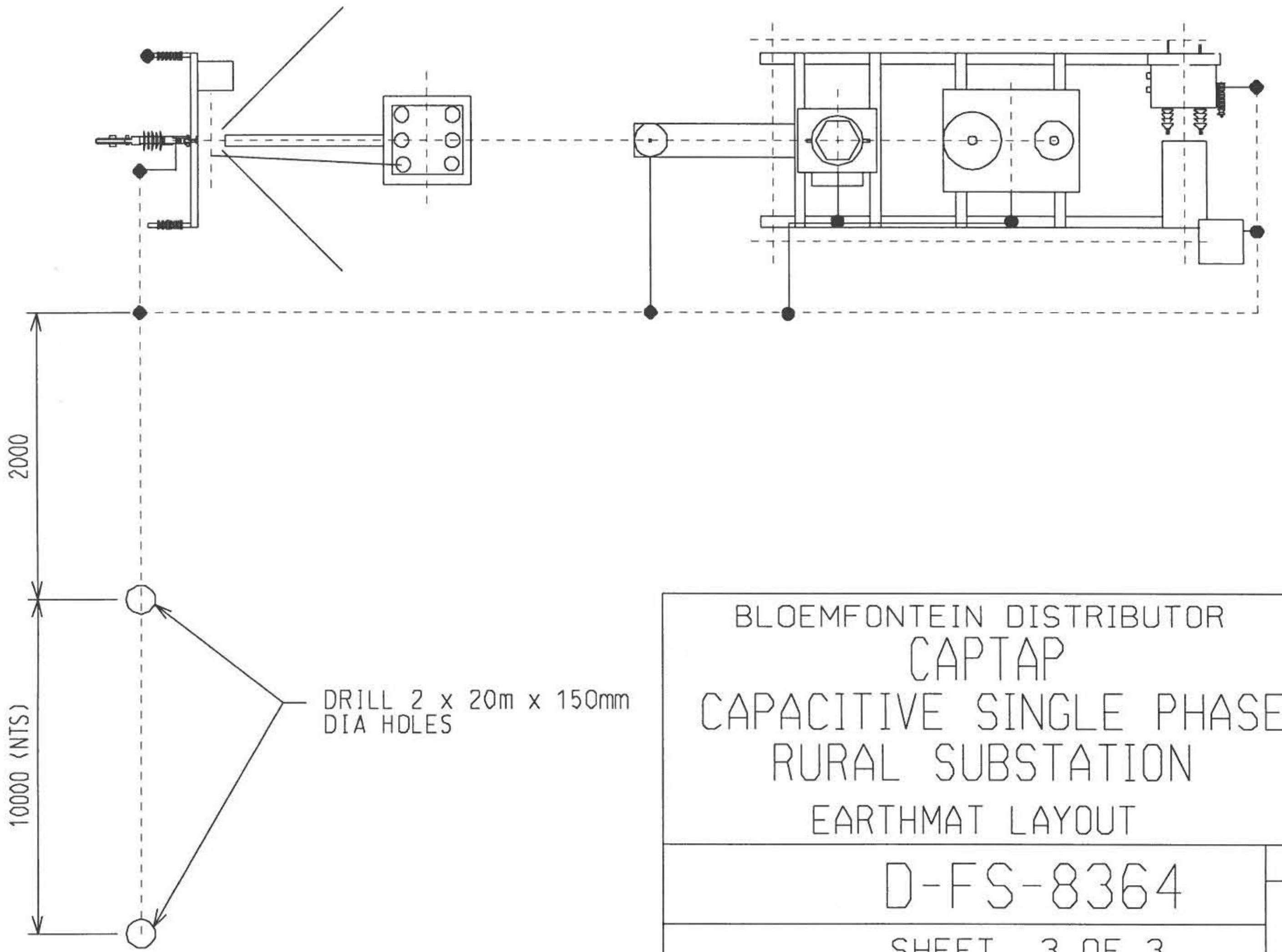
1. SUPPORT CAPS FIXING HOLES TO BE DRILLED ON SITE. (18mm DIA. HOLES FOR M16 BOLTS)

2. CONSTRUCTION TO ASCERTAIN GROUND CONDITIONS AND SHORTEN POLES ACCORDINGLY. POLES TO BE PLANTED 1.8m DEPTH (MIN).

3. SUPPORT FOR CAP. BANK - EX APOLLO PILOT SUBSTATION.

CAPTAP CAPACITIVE SINGLE PHASE RURAL SUBSTATION GENERAL ARRANGEMENT		
	D-FS-8364	REV
	SHEET 1 OF 3	2


SECTION A-A
FOX CONDUCTOR
WOLF CONDUCTOR
SCREEN WIRE
FOX CONDUCTOR
INLINE LINK
EARTH SWITCH
SCREEN WIRE TO BE CONNECTED
TO MAIN EARTH WIRE
NEUTRAL PHASE TO
22kV NEUTRAL CT
LV CABLE
TO NEUTRAL CT
PROTECTION
BOX
7900
4900
1500
5000
6700
9050
SECTION B-B
NEUTRAL
FOX CONDUCTOR
LIVE
FOX CONDUCTOR
WOLF CONDUCTOR
NEUTRAL CT
EARTH WIRE
PROTECTION BOX
FILTER BOX
1500
BLOEMFONTEIN DISTRIBUTOR
CAPTAP
CAPACITIVE SINGLE PHASE
RURAL SUBSTATION
SECTIONS
D-FS-8364
SHEET 2 OF 3
REV
2



BLOEMFONTEIN DISTRIBUTOR

CAPTAP

CAPACITIVE SINGLE PHASE RURAL SUBSTATION

EARTHMAT LAYOUT

D-FS-8364	REV 2
SHEET 3 OF 3	

Appendix E : Pilot CAPTAP Substation Protection Drawings

This protection drawings originated from the Prototype CAPTAP substation and were modified with the building of the Pilot CAPTAP substation. The drawings are now Eskom standard protection drawings for future CAPTAP substations.

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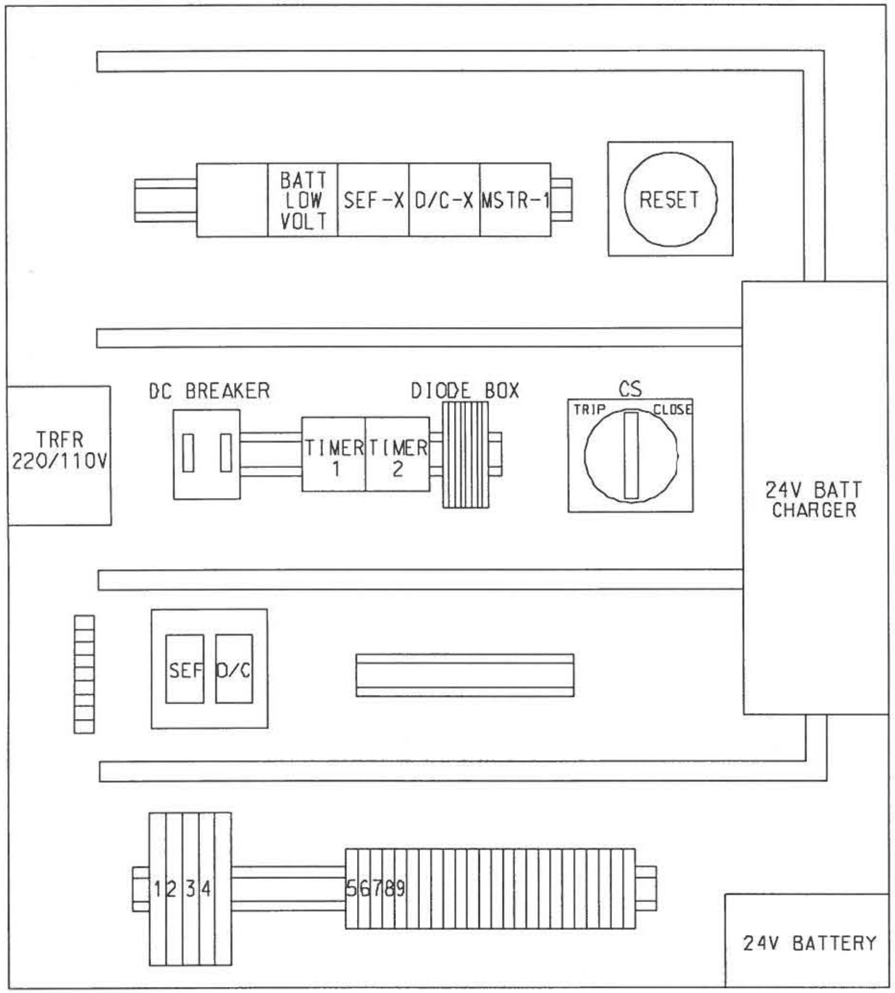


CAPTAP

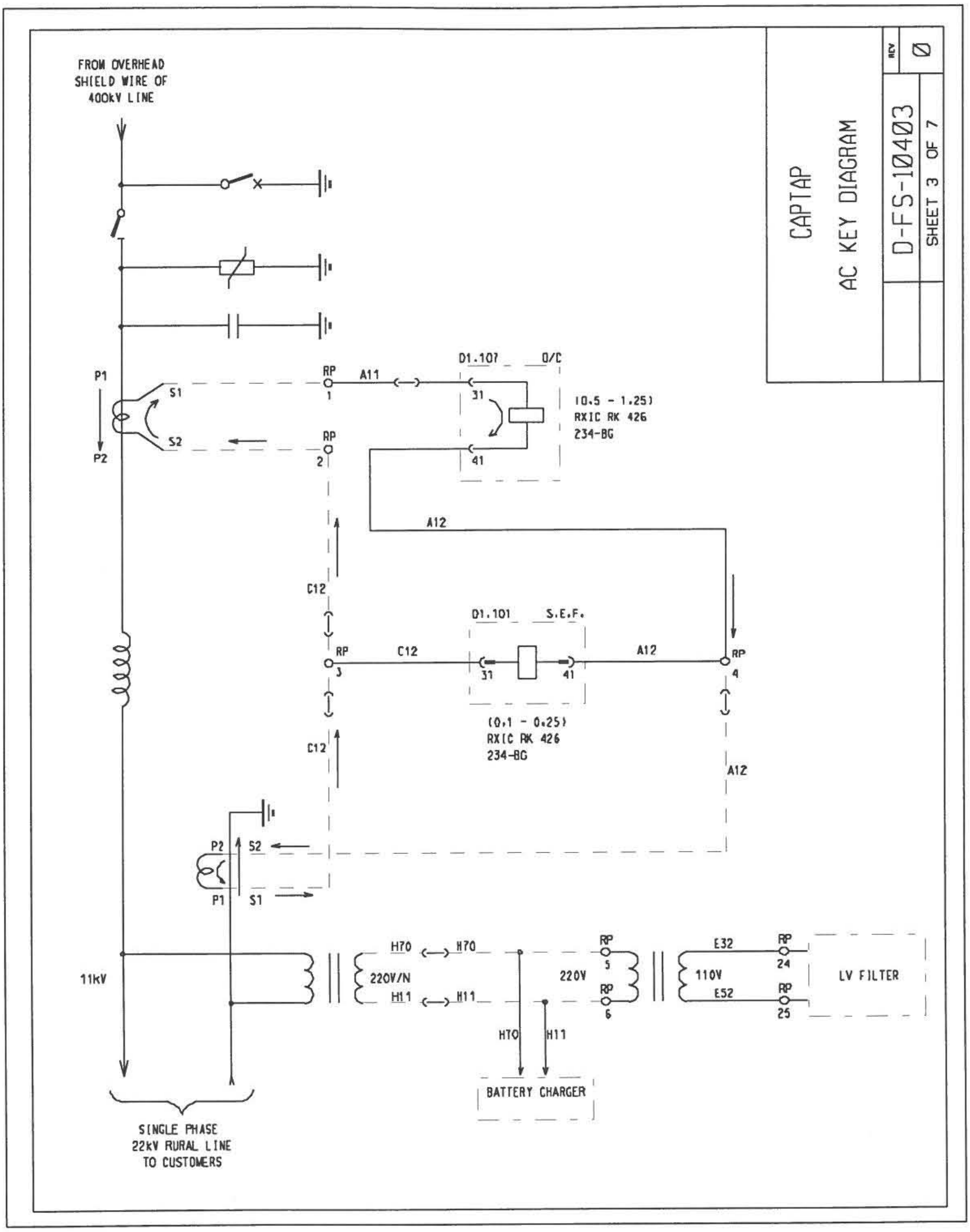
PANEL LAYOUT

	D-FS-10403	REV
	SHEET 1 OF 7	0

-99-

LOCATION	TYPE	MODEL	DESCRIPTION	QTY	PRICE	SUPPLIER
1.1-8	OMRON MK ACCESSORIES	MK2KP PF113A	24V DC MAGNETIC LATCHING RELAY CONNECTING SOCKET FOR ABOVE	8 8	R 140.00	YELLAND BBT (832 2061)
1.9	OMRON H3CA ACCESSORIES	H3CA-A P2CF-11	MULTI PURPOSE TIMER RELAY 12V DC SUPPLY CONNECTING SOCKET FOR ABOVE	1 1	R 200.00	YELLAND BBT (832 2061)
1.12	SANTON/ ROTARY		CONTROL SWITCH - 3 POLE , 3 WAY , SPRING RETURN TO NEUTRAL	1		
1.11			PUSHBUTTON - ONE POLE	1		
1.10	CONTA-CLIP	DM8-5	DIODE MODULE	1		SIDTECH (NEVILLE CLARK) (472 2033)
	KLIPPON	SAF4 RSF1	TERMINALS TERMINALS	20 6		
			DIN RAIL	1		
	SIEMENS	5SN09202	MINITURE CIRCUIT BREAKER	1		SIEMENS (STD. PRODUCT)
	ASEA					
			2 POLE			
1.107	RXIC RK426	234-BG	CURRENT RELAY (0, 5 - 1, 25A)	1	R 950.00	BBT RELAYS (HARRY GILL)
1.101	RXIC RK426	234-BG	CURRENT RELAY (0, 1 - 0, 25A)	1	R 950.00	(012 3189911)
	ASEA					
	RX221		PANEL BASS (SURFACE MOUNT)	1	R 227.00	BBT RELAYS (HARRY GILL) (012 3189911)
			BATTERY CHARGER (INPUT) 22V AC/24V DC/BATTERY) (STANDARD, OFF THE SELF CAR BATTERY CHARGER) BATTERY 24V DC 60 AMPHOUR (CAR BATTERY) METAL ENCLOSURE (IP55) TO HOUSE ALL OF THE ABOVE EQUIPMENT	1 1 1		

CAPTAP DESCRIPTION OF RELAY'S	
D-FS-10403 SHEET 2 OF 7	REV Ø


FROM OVERHEAD SHIELD WIRE OF 400kV LINE
P1
S1
S2
P2
RP 1
A11
D1.107
O/C
31
41
(0.5 - 1.25)
RXIC RK 426
234-BG
RP 2
A12
C12
D1.101
S.E.F.
RP 3
C12
31
41
A12
RP 4
(0.1 - 0.25)
RXIC RK 426
234-BG
C12
A12
P2
S2
P1
S1
11kV
H70
H70
220V/N
H11
H11
220V
RP 5
RP 6
H70
H11
110V
E32
E52
RP 24
RP 25
LV FILTER
BATTERY CHARGER
SINGLE PHASE 22kV RURAL LINE TO CUSTOMERS
CAPTAP
AC KEY DIAGRAM
D-FS-10403
SHEET 3 OF 7
REV
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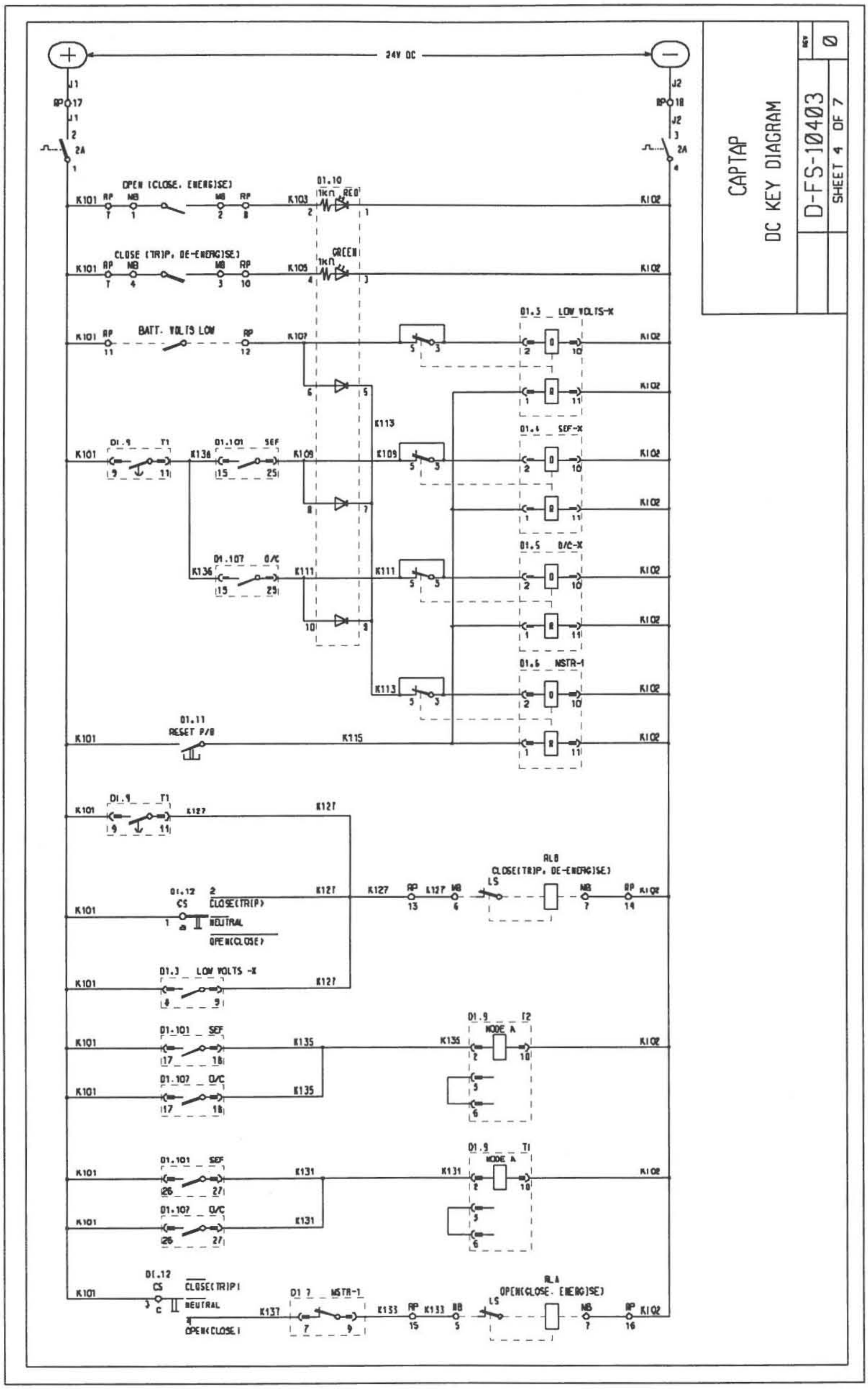

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1. RELAY PANEL TO LINK

RP	CORE	CORE NO	LINK
7	1	K101	1
8	2	K103	2
7	3	K101	4
10	4	K105	3
19	5	K134	8
13	6	K127	6
14	7	K102	7
15	8	K133	5
	9	SPARE	
	10	SPARE	
	11	SPARE	
	12	SPARE	

2. RELAY PANEL TO CT

RP	CORE	CORE NO	LINK
1	RED	A11	S1
2	BLACK	C12	S2
	WHITE	SPARE	
	BLUE	SPARE	

3. RELAY PANEL TO FILTER

RP	CORE	CORE NO	LINK
5	RED	L	L
6	BLACK	N	N

4. RELAY PANEL TO N-CT

RP	CORE	CORE NO	LINK
3	RED	C12	S1
4	BLACK	A12	S2
	WHITE	SPARE	
	BLUE	SPARE	

5. RELAY PANEL TO TRFR

RP	CORE	CORE NO	LINK
5	RED	A1	A1
6	BLACK	A3	A3

CAPTAP

CABLING DIAGRAM

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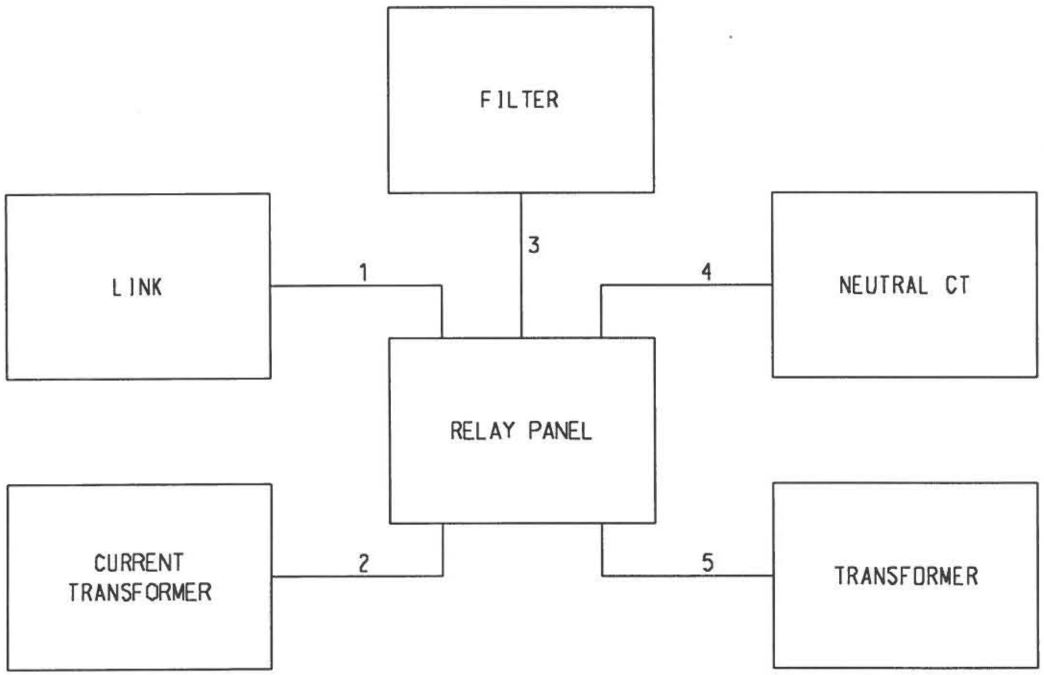
	SHEET 5 OF 7	0



NO	DESCRIPTION
1	12 CORE 4mm CABLE
2	4 CORE 4mm CABLE
3	2 CORE 16mm CABLE
4	4 CORE 4mm CABLE
5	2 CORE 16mm CABLE

CAPTAP

CABLE BLOCK

D-FS-10403

SHEET 6 OF 7

REV

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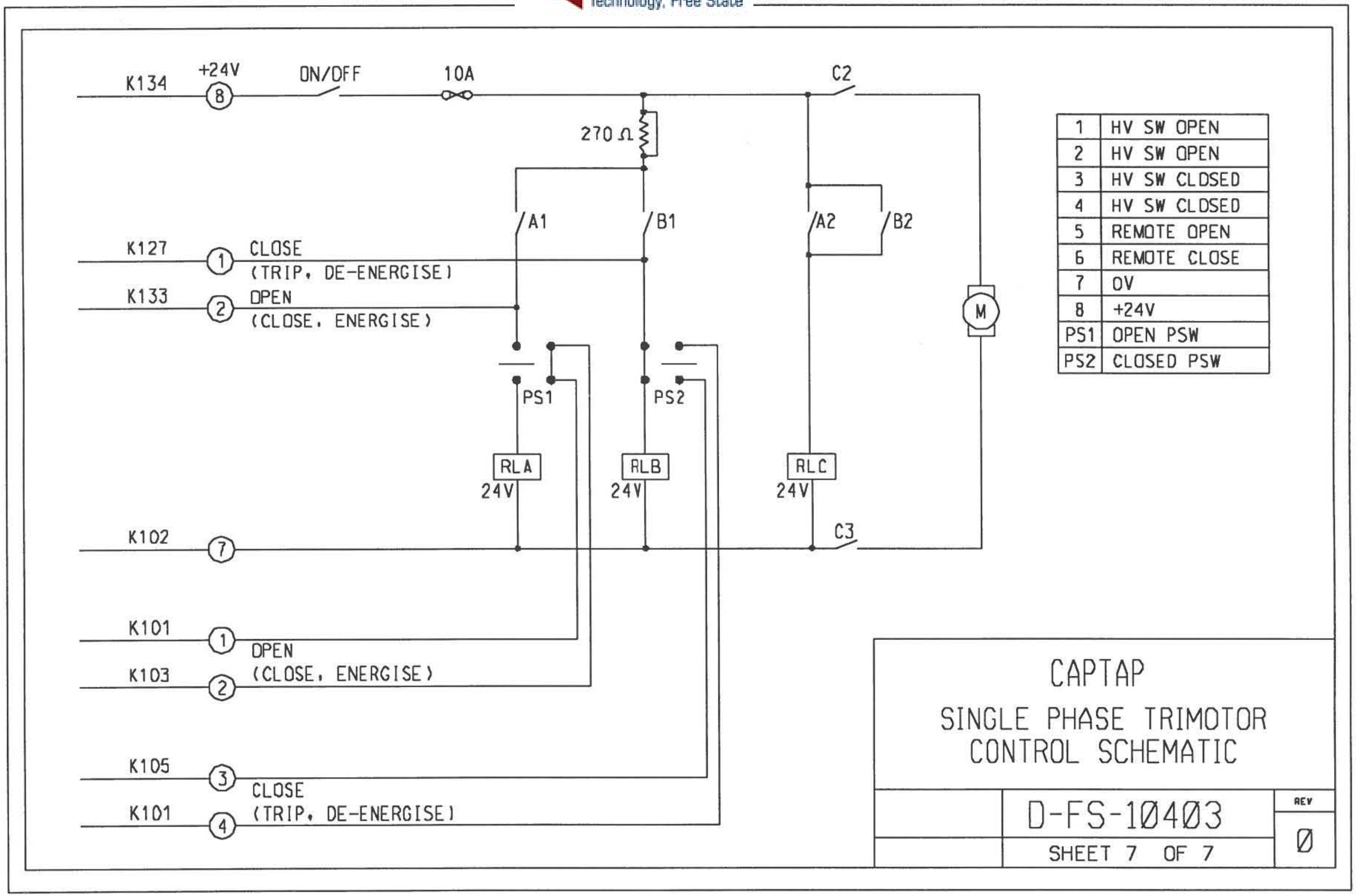

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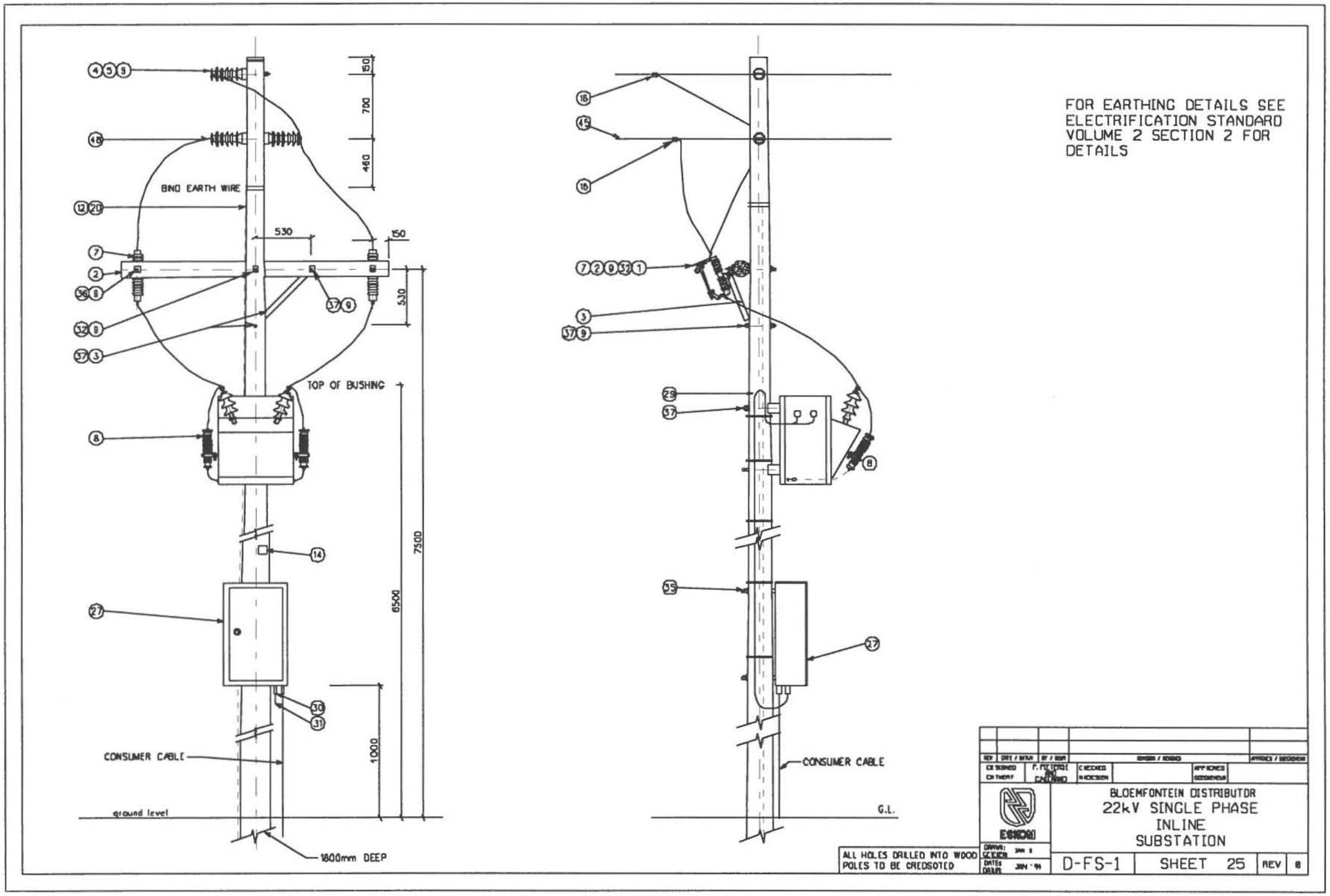
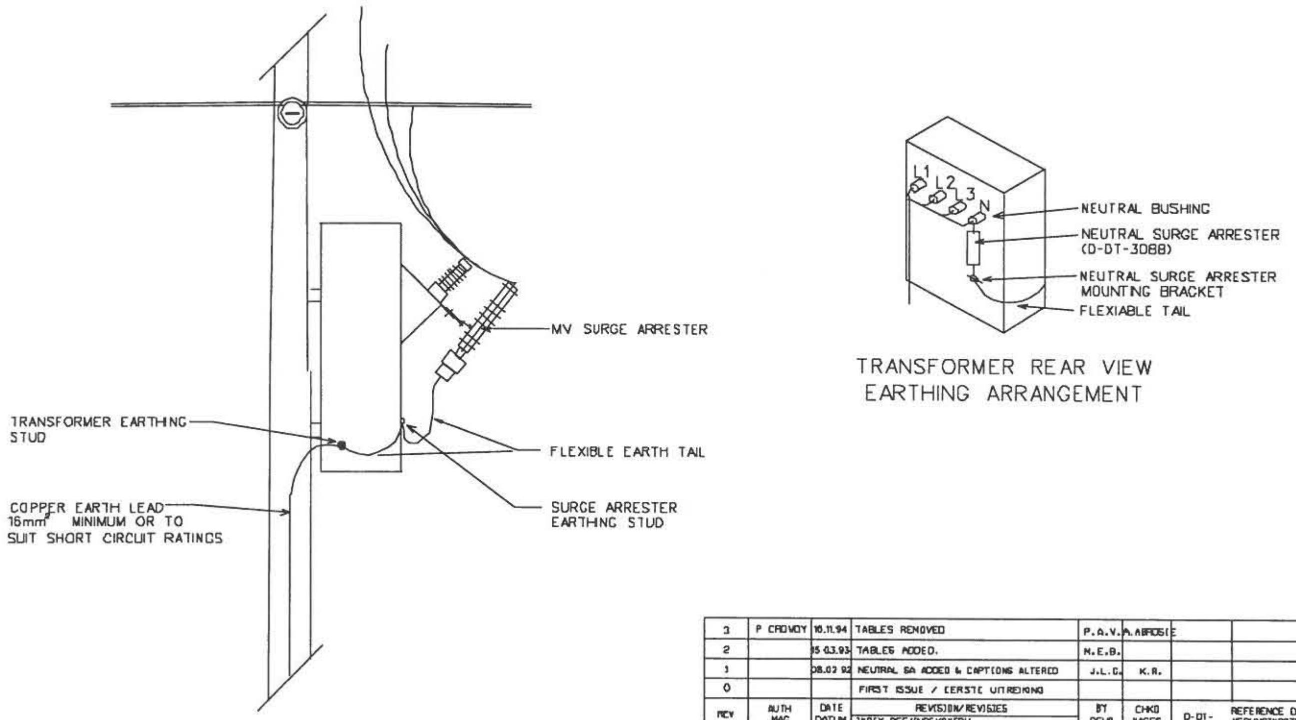
Appendix F : Customer Supply Points

The two customer supply points, Poortjie Nr. 1 and Poortjie No.2, were constructed according to Eskom standard rural supply points. The supply points were properly earthed and tariff meters were installed to measure the energy used by the customer.


FOR EARTHING DETAILS SEE ELECTRIFICATION STANDARD VOLUME 2 SECTION 2 FOR DETAILS
BIND EARTH WIRE
TOP OF BUSHING
CONSUMER CABLE
ground level
1800mm DEEP
G.L.
ALL HOLES DRILLED INTO WOOD POLES TO BE CREOSOTED
BLOEMFONTEIN DISTRIBUTOR
22kV SINGLE PHASE
INLINE
SUBSTATION
ESKOM
D-FS-1
SHEET 25
REV



REV	AUTH MAG	DATE DATUM	REVISION/REVISIES INDEX REF/INDEKSVERW	BY DEUR	CHKD NAGES	D-DT-	REFERENCE DRAWINGS VERWYSINGSTEKENINGE
3	P CRONOY	10.11.94	TABLES REMOVED	P.A.V.	A.ABROSIE		
2		15.03.93	TABLES ADDED.	M.E.B.			
1		08.02.92	NEUTRAL SA ADDED & CAPTIONS ALTERED	J.L.C.	K.R.		
0			FIRST ISSUE / EERSTE UITREIKING				

ORG.TEK REGISTR

ESKOM

ESKOM
EARTHING
CONNECTIONS
FOR
SURGE ARRESTERS

CHKD NAGES	K.ROZMAREK	91.10.21			
DRAWN GETEKEN	CTR • DTS JL CROBLER	91.10.21	APPROVED S.A CILLIERS	CAD.REF. CHALL/EARTHING	D-DT-0628
SCALE SKAAL	NTS		10.01.1994	FILE No. 0828	REV 3

Appendix G : Control Procedures for the CAPTAP Substation

These procedures were requested by the Eskom Control Centre in Kimberly, in order to obtain a step-by-step instruction list to energise and de-energise the CAPTAP substation. This was necessary due to the rather unusual method of energising and de-energising of the CAPTAP substation (i.e. opening the earth switch to energise!)

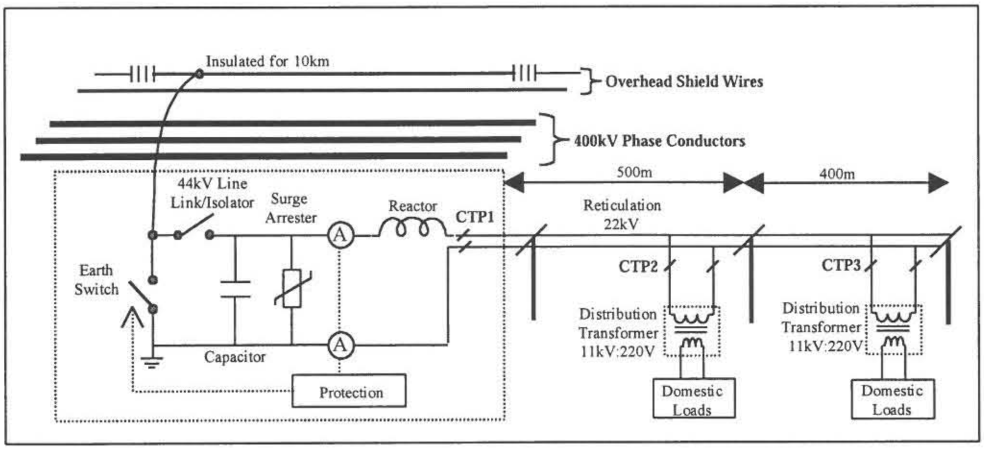
Procedure to De-Energise, Isolate and Earth

- Switch 44kV earth-switch in protection panel to the "de-energise" position, to close the 44kV earth-switch, thereby de-energising the system (Control switch is spring-operating and will go back to the original position)
- Check earth-switch to be open.
- Open the 44kV Line-link
- Open CTP1 link (To consumer)
- Safety test and earth
  - on 400kV Line-side of 44kV Line-link/Isolator
  - on capacitor side of 44kV Line Link/Isolator
  - on Reactor side of CPT1 links/Isolator
  - on consumer side of CPT1 links/Isolator
  - a total of 4 earths to apply

Procedures to Energise the CAPTAP substation

- Remove earth fromcomsumer side of CTP1 links/Isolator
- Remove earth from Reactor side of CPT1 links/Isolator
- Remove earth from capacitor side of Line Link/Isolator
- Remove earth from 400kV Line-side of 44kV Line-link/Isolator
- Close 44kV Line-link/Isolator
- Switch 44kV earth-switch in protection panel to the "energise" position, to open the 44kV earth-switch, thereby energising the system. (Control switch is spring-operated and will go back to the original position)
- Check earth-switch to be open
- Close CTP1 link

Hand out the system to the Authorised person

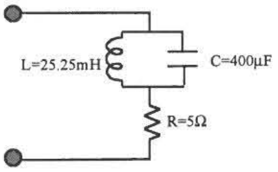


Appendix H : Specifications for CAPTAP Equipment

The specifications were specified for the Prototype CAPTAP substation, re-evaluated for the Pilot CAPTAP substation and recommended for future CAPTAP substations. The reason for the 44kV insulation level was due to the high voltages that were experienced across the reactor and capacitor during full load conditions.

Specifications for CAPTAP Equipment

1. Low-voltage Filter



The reactor and capacitor must be resonant at 50Hz (ie. XL = Xc) The filter will be used to damp out transients while not absorbing much energy during steady state 50Hz conditions.

1.1 Inductor specifications

Maximum continuous operating voltage (shunt)	120V(rms)
Continuous operating current	19A(rms)
Maximum operating current	75°C
Minimum X/R ration at operating temperature	30
Inductance	25.25mH
Knee-point voltage (minimum)	150V(rms)

1.2 Capacitor Details

Maximum continuous operating voltage	120V(rms)
3 second temporary over voltage	240V(rms)
Capacitance	400µF

1.3 Resistor Details

Resistance	5Ω
Continuous power dissipation capability	500W

1.4 Insulation for total installation

50 Hz 1 min. withstand	1000V(rms)
Impulse withstand (1.2/50µs)	2000V(peak)

2. Special class X Neutral current transformer

The CT should be suitable for pole mounting and should be supplied with all the necessary brackets.

The primary coil should have one termination on the top and the other on the bottom of the CT. The secondary winding should have its terminations on the bottom of the CT.

Specifications

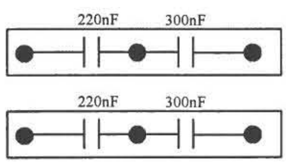
Turns Ratio	1:2.3
Class	X
Minimum secondary knee-point voltage	60 V
Maximum secondary magnetising current	120mA
Maximum secondary resistance	1.0Ω
Maximum continuous primary current	2.5A
Short-time current (3sec.)	10A
Primary winding insulation level (50Hz)	6.6kV

2. Special class X 44kV current transformer

Turns Ratio	1:2.3
Class	X

This must be a 44kV CT but must be able to measure current with a very low turns ratio.

3. Single-phase Capacitor Bank



Continuous voltage rating (per can ie. 220+300)	50kV
60 sec, withstand voltage	95kV
Lightning Impulse withstand	250kV

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4. Series compensation Reactor

Type of cooling		ONAN
Continuous current rating		2.3A
Overload current (5 min.)		5A
Maximum internal resistance at 75°C		283Ω
Total inductance	tap 1	40H
	tap2	45H
	tap3	50H
Fully insulated		
Voltage withstand (1min. 50Hz)		140kV(rms)
Impuls voltage withstand (1.2 mic. Sec.)		350kV(rms)

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